



The Effects of Ship Noise on Marine Mammals—A Review

Christine Erbe^{1*}, Sarah A. Marley², Renée P. Schoeman³, Joshua N. Smith⁴, Leah E. Trigg⁵ and Clare Beth Embling⁵

¹ Centre for Marine Science and Technology, Curtin University, Perth, WA, Australia, ² Institute of Marine Sciences, University of Portsmouth, Portsmouth, United Kingdom, ³ School of Environmental Sciences, Nelson Mandela University, Port Elizabeth, South Africa, ⁴ Harry Butler Institute, Murdoch University, Perth, WA, Australia, ⁵ School of Biological and Marine Sciences, University of Plymouth, Plymouth, United Kingdom

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*Correspondence:

Christine Erbe
c.erbe@curtin.edu.au

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The number of marine watercraft is on the rise—from private boats in coastal areas to commercial ships crossing oceans. A concomitant increase in underwater noise has been reported in several regions around the globe. Given the important role sound plays in the life functions of marine mammals, research on the potential effects of vessel noise has grown—in particular since the year 2000. We provide an overview of this literature, showing that studies have been patchy in terms of their coverage of species, habitats, vessel types, and types of impact investigated. The documented effects include behavioral and acoustic responses, auditory masking, and stress. We identify knowledge gaps: There appears a bias to more easily accessible species (i.e., bottlenose dolphins and humpback whales), whereas there is a paucity of literature addressing vessel noise impacts on river dolphins, even though some of these species experience chronic noise from boats. Similarly, little is known about the potential effects of ship noise on pelagic and deep-diving marine mammals, even though ship noise is focused in a downward direction, reaching great depth at little acoustic loss and potentially coupling into sound propagation channels in which sound may transmit over long ranges. We explain the fundamental concepts involved in the generation and propagation of vessel noise and point out common problems with both physics and biology: Recordings of ship noise might be affected by unidentified artifacts, and noise exposure can be both under- and over-estimated by tens of decibel if the local sound propagation conditions are not considered. The lack of anthropogenic (e.g., different vessel types), environmental (e.g., different sea states or presence/absence of prey), and biological (e.g., different demographics) controls is a common problem, as is a lack of understanding what constitutes the ‘normal’ range of behaviors. Last but not least, the biological significance of observed responses is mostly unknown. Moving forward, standards on study design, data analysis, and reporting are badly needed so that results are comparable (across space and time) and so that data can be synthesized to address the grand unknowns: the role of context and the consequences of chronic exposures.

Keywords: auditory masking, chronic noise exposure, marine watercraft, ship noise emission, commercial shipping, marine mammal, behavioral response

INTRODUCTION

Marine traffic in the world's oceans is increasing. This includes watercraft ranging from small boats to large ships. Commercial ships are increasing in number as well as size, linked to overall economic growth (United Nations Conference on Trade and Development [UNCTAD], 2018). Between World War II and 2008, the global number of ships rose by a factor 3.5 and the total gross tonnage by a factor 10 (Frisk, 2012). Based on satellite altimetry, global ship density increased by a factor 4 between 1992 and 2012, with the greatest increase in the Indian Ocean (Tournadre, 2014). Ship noise is rising concomitantly. In fact, ships have become the most ubiquitous and pervasive source of anthropogenic noise in the oceans. Ship traffic is responsible for the steady rise in ambient noise at low frequencies (10–100 Hz) in many ocean regions—a rate that has been reported to be as high as 3 dB/decade (Andrew et al., 2002, 2011; Chapman and Price, 2011; Miksis-Olds et al., 2013; Miksis-Olds and Nichols, 2016).

Concern about the potential effects of ship noise on marine mammals is not recent, but instead has been raised for decades (e.g., Payne and Webb, 1971; Myrberg, 1978; Geraci and St Aubin, 1980). As ship noise peaks in the low frequencies, early studies primarily focused on low-frequency specialist species such as mysticetes (i.e., baleen whales) (e.g., Eberhardt and Evans, 1962; Cummings and Thompson, 1971). Mysticetes produce and use sound at the frequencies emitted by large ships, and they are considered to be more sensitive at these low frequencies than are other marine mammals (e.g., Parks et al., 2007b; Cranford and Krysl, 2015). However, ships also emit significant energy at higher frequencies (tens of kHz) (e.g., Arveson and Vendittis, 2000; Hermanssen et al., 2014; Veirs et al., 2016), and so odontocetes (i.e., toothed whales, dolphins, and porpoises), which specialize in high-frequency sound usage, can also be affected (e.g., Marley et al., 2017b). Not only commercial ship traffic but also numbers of small boats have been increasing around the world. For example, the number of registered recreational vessels in the United States increased by 1% per annum between 1980 and 2017 (U.S. Department of Homeland Security, 2018). In the state of Florida, there is approximately one registered recreational boat per 17 people (Sidman and Fik, 2005). Similarly, parts of Australia saw increases of 3% per annum between 1999 and 2009 (Nsw Government Maritime, 2010). In Sydney Harbour, 70% of overall vessel traffic is comprised of recreational boats (Widmer and Underwood, 2004). Noise from small boats peaks at higher frequencies (e.g., Erbe, 2013; Erbe et al., 2016b) at which coastal odontocetes are more sensitive (e.g., Houser and Finneran, 2006).

The noise field around a boat or ship is not isotropic (i.e., it is not the same in all directions; e.g., Arveson and Vendittis, 2000). It depends on source frequency and the environment in which the vessel travels, and it changes with vessel speed, load, size, and other factors (e.g., Ross, 1976; Urick, 1983). Consequently, it is not straightforward to translate acoustic recordings made in one environment to others. Obtaining quality recordings of watercraft noise is a science of its own, with numerous flaws that are commonly unrecognized in the literature.

Similarly, determining the responses of marine mammals to watercraft noise has numerous challenges, including constraints

in experimental design; variability in species-, population-, and individual-specific characteristics and responses; and context-specific factors that may need to be considered. For example, many studies suffer bias from observer presence in that the majority of marine mammal studies are, by necessity, vessel-based. This introduces a potential source of bias from the presence of the research vessel, as well as the noise it creates. Furthermore, many studies struggle to differentiate between the effects of vessel presence and vessel noise, resulting in confounding explanatory variables. Even if researchers can be confident in noise as the source of disturbance, measurements are often inconsistent between studies, thus complicating comparisons. Animal behavioral responses can also take many forms. Due to the challenges associated with studying these fast-moving, far-ranging, often-submerged animals, the majority of marine mammal behavioral response studies in the wild concentrate on visible changes to physical behavior at the sea surface, such as changes in occurrence or cessation of certain activities. Far fewer consider a combination of behavioral changes, including acoustical behaviors. The resulting knowledge gaps, biases, and uncertainties may be minimized by standardization and interdisciplinary cooperation.

In fact, the effects of watercraft noise on marine mammals is an interdisciplinary field: Sound generation, propagation, measurement, and modeling are physics problems, yet monitoring animals, determining impacts, and understanding biological significance are biological problems. Misinformation and miscommunication have led to numerous issues with underwater acoustic quantities, units, recording and reporting, as well as experimental design, statistical analysis, and interpretation. This review provides an overview of the field of watercraft noise impacts on marine mammals, explains the fundamental physical and biological concepts, highlights common issues and problems, identifies data gaps, and discusses research needs.

GENERATION AND PROPAGATION OF WATERCRAFT NOISE

There is a large variety of motorized boats and ships, such as recreational boats, passenger and car ferries, high-speed hovercraft, cruise ships, tug boats, dredges, dry and liquid cargo vessels, fishing vessels, oil and gas production platforms, research vessels, naval ships, submarines, etc. All of these produce noise. Source levels¹ of 130–160 dB re 1 μ Pa m have been reported for small watercraft such as jetskis and rigid-hulled inflatable boats

¹In the case of ship noise, source levels (SL) are typically given as a root-mean-square (rms) sound pressure level (SPL). The sound pressure is recorded at some distance (i.e., in the far-field) from the vessel, and the root-mean-square is computed (i.e., literally squaring the pressure samples, summing, dividing by their number, and taking the square-root). Applying “20 log₁₀()” converts the rms sound pressure to a level quantity (i.e., SPL) in the far-field. Propagation loss is typically modeled and a propagation loss term is added, yielding a (monopole) SL referenced to a distance of 1 m from the source. SPL and SL are thus expressed in dB relative to 1 μ Pa and 1 μ Pa m, respectively. Note that the notation of ‘@ 1 m’ is common in the literature but deprecated by the ISO (International Organization for Standardization, 2016, 2017).

(Erbe, 2013; Erbe et al., 2016b). Large and powerful watercraft such as ferries, container ships, and icebreakers have source levels of 200 dB re 1 μ Pa m and more (e.g., Erbe and Farmer, 2000; Simard et al., 2016; Gassmann et al., 2017). Source levels may vary by 20–40 dB within a ship class due to variability in design, maintenance, and operational parameters such as speed (Simard et al., 2016; Joy et al., 2019).

The strongest noise source is typically the propeller when it cavitates (Ross, 1976). Propeller cavitation involves the formation of bubble clouds behind the propeller. Bubbles of all sizes are created, then grow, vibrate and collapse, producing an overall broadband noise spectrum that ranges from a few Hz to over 100 kHz (Ross, 1976). Traveling at low speed and/or great depth (hence pressure; e.g., submarines) can reduce and avoid propeller cavitation noise. Cavitation noise increases with vessel speed, size, and load (e.g., Ross, 1976; Urick, 1983; Scrimger and Heitmeyer, 1991; Hamson, 1997; Trevorrow et al., 2008; Simard et al., 2016). Cavitation noise is typically amplitude-modulated by the propeller blade rate (i.e., the number of propeller blades times the number of rotations per second; Ross, 1976). ‘Propeller singing’ refers to narrow-band noise that is a result of vibrating propeller blades. The engine and any machinery onboard a ship also produce noise, and this may couple well into the water through the ship’s hull (Urick, 1983). The engine generates narrow-band noise consisting of the engine firing-rate plus overtones (Arveson and Vendittis, 2000). Furthermore, hydrodynamic flow past the hull can lead to vibration of appendages or cavities generating additional narrow-band noise (Urick, 1983). Overall, the noise spectrum emitted by a ship may have multiple sources that contribute noise from different locations about the ship, at different frequencies and into different directions—leading to a complicated and dynamic noise field.

The noise field varies with frequency and angle about a vessel (Arveson and Vendittis, 2000; Trevorrow et al., 2008; Gassmann et al., 2017). Given that boats and ships operate at the water surface and the propeller sits, at maximum, a few meters below the surface, emitted noise reflects at the water surface leading to a strongly downward-directed noise emission pattern (e.g., Gassmann et al., 2017). In physical terms, the source of the watercraft noise and its image source (in air) create a dipole radiation pattern. This means that watercraft noise radiates very well to great depth in the ocean. Radiation in the horizontal plane, near the sea surface, is greatly reduced because of destructive interference of the image source with the real source (i.e., the Lloyd’s mirror effect; note that the interference pattern is frequency-dependent). In addition, the hull may shield sound propagation from the propeller in the forward direction. These acoustic radiation phenomena might explain why marine mammals that spend a lot of time at the water surface are prone to vessel strike (e.g., right whales and sirenians) and why bow-riding marine mammals (Würsig, 2018) are not disturbed by the vessel’s noise (Gerstein et al., 2005).

As a vessel travels through different environments, from coastal to offshore waters, its noise field changes. In shallow water, the propagating noise repeatedly interacts with the water surface and seafloor, where it is reflected, scattered, and partly

absorbed (e.g., Cole and Podeszwa, 1967). The directionality of the noise field is highly variable. In deep water, the directionality is dipolar (i.e., strongly downward) and interactions with, and hence acoustic energy losses at, the seafloor and sea surface are reduced. The noise from watercraft traveling in deep water easily couples into the deep sound channel [i.e., the so-called Sound Fixing And Ranging (SOFAR) channel; e.g., Williams and Horne, 1967; Shockley et al., 1982], where it can traverse entire oceans with very little acoustic energy loss. The noise from watercraft traveling over sloping bathymetry (such as the continental slope) can enter the SOFAR channel with just one seafloor reflection (**Figure 1**). Animals in coastal versus offshore waters or at low versus great depth may experience quite different noise fields—even at the same range from the same vessel.

IMPACTS OF WATERCRAFT NOISE ON MARINE MAMMALS

The effects of underwater noise from anthropogenic activities on marine mammals have been summarized in several works and include the following: behavioral responses, acoustic interference (i.e., masking), temporary or permanent shifts in hearing threshold (TTS, PTS), and stress (e.g., Richardson et al., 1995; Nowacek et al., 2007; Erbe et al., 2018). Acute effects on individual animals are more easily observed, more frequently published, and hence better understood than long-term effects on populations from chronic exposures. Watercrafts are the primary source of chronic noise exposures on marine mammals.

We set out to review the effects of watercraft noise on marine mammals by compiling the literature from a Web of Science search², augmented by our personal libraries. The following criteria had to be met for articles to be included in the review. Studies:

- must have dealt with marine vessels;
- must have dealt with marine mammals in water (hence excluding hauled-out pinnipeds);
- may have focused on one or the other;
- must have measured, observed, modeled, or estimated responses (i.e., articles that addressed the potential effects of vessel noise only in the Discussion were excluded); and
- did not need to have measured or modeled source levels or received levels of noise.

A total of 154 articles were included in this review. A rapid growth in the number of publications has occurred since the year 2000 (**Figure 2**). Forty-seven marine mammal species have been studied. The most studied species are the bottlenose dolphin (*Tursiops truncatus*), humpback whale (*Megaptera novaeangliae*), and then beluga whale (*Delphinapterus leucas*) (**Figure 3**). **Figure 4** maps the different study sites by species.

²Web of Science search information: Search string: TS = (ship\$ OR boat\$ OR vessel\$) AND TS = noise AND TS = (marine mammal\$ OR whale\$ OR porpoise\$ OR dolphin\$ OR seal\$ OR sea lion\$ OR sealion\$ OR dugong\$ OR manatee\$). Years searched: 1972–2019. Number of returned articles: 504.

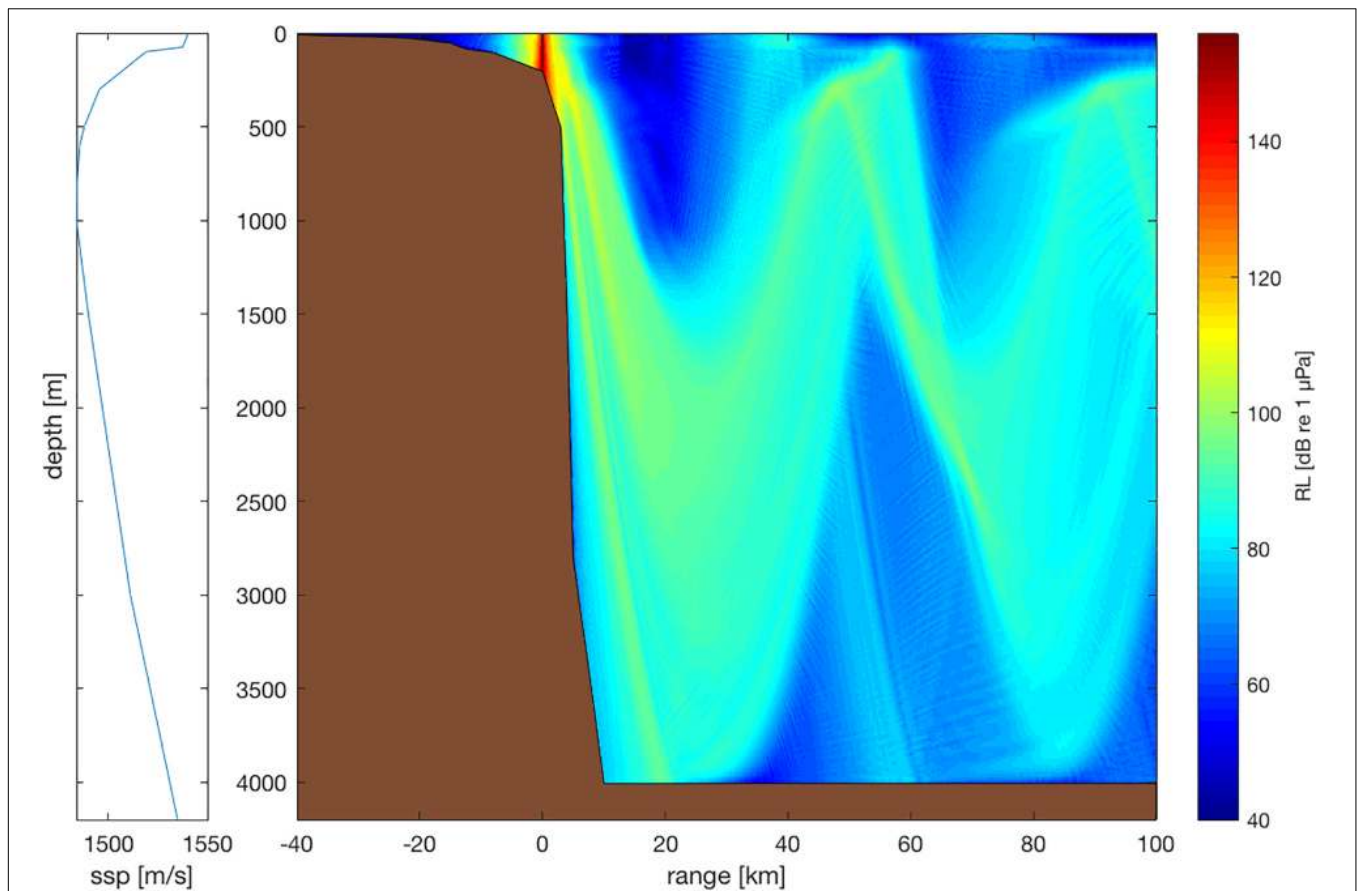


FIGURE 1 | Sketch of the noise field of a cruise ship at the continental slope [at location (0) 0]. Source spectrum representative of vessel class ‘L5’ (length: 156 m, speed: 15 knot, source level: 191 dB re 1 μ Pa m; Erbe et al., 2012). Propagation loss model: RAMGeo in AcTUP V2.8 (<https://cmst.curtin.edu.au/products/underwater/>). Equatorial sound speed profile (ssp; **left** panel; taken from Shockley et al., 1982). Seafloor modeled as hard, dense limestone (Hamilton, 1980). No ambient noise is included in this plot. Broadband received levels (RL) are color-coded using the scale in the **right** panel. The dipole radiation pattern (i.e., most energy radiating downward) is clearly visible. While sound energy propagates poorly into shallow water (with received levels rapidly decreasing with increasing range), it propagates well (i.e., with little loss) into deep water.

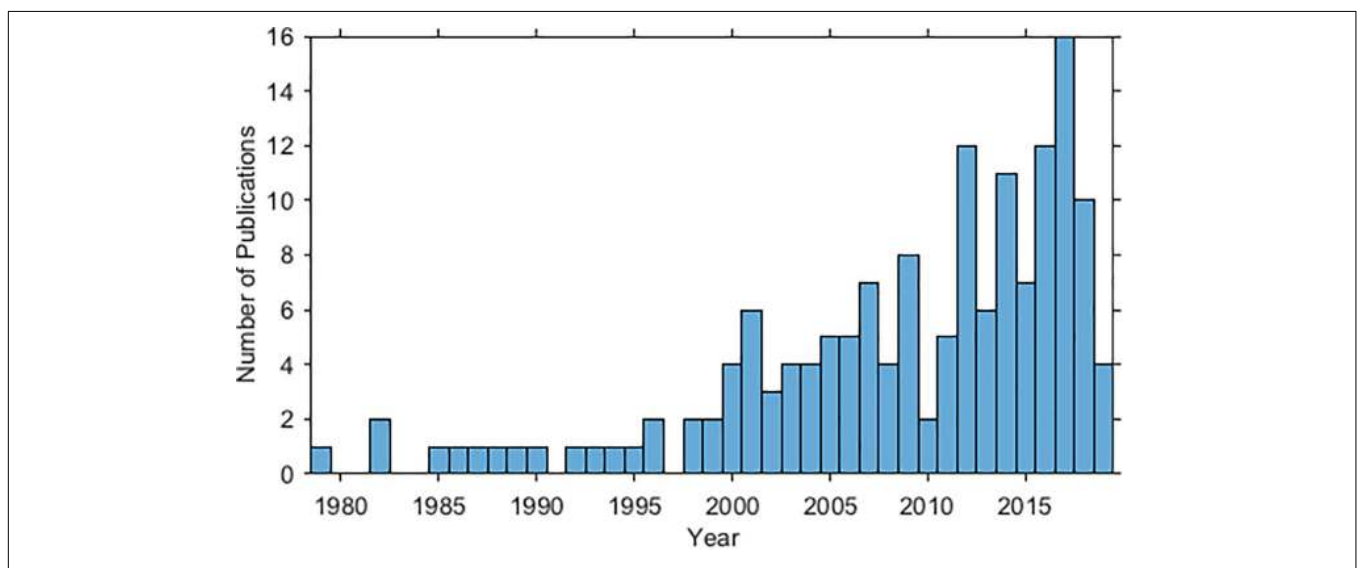


FIGURE 2 | Histogram of the number of publications meeting search criteria—by year (until mid-2019).

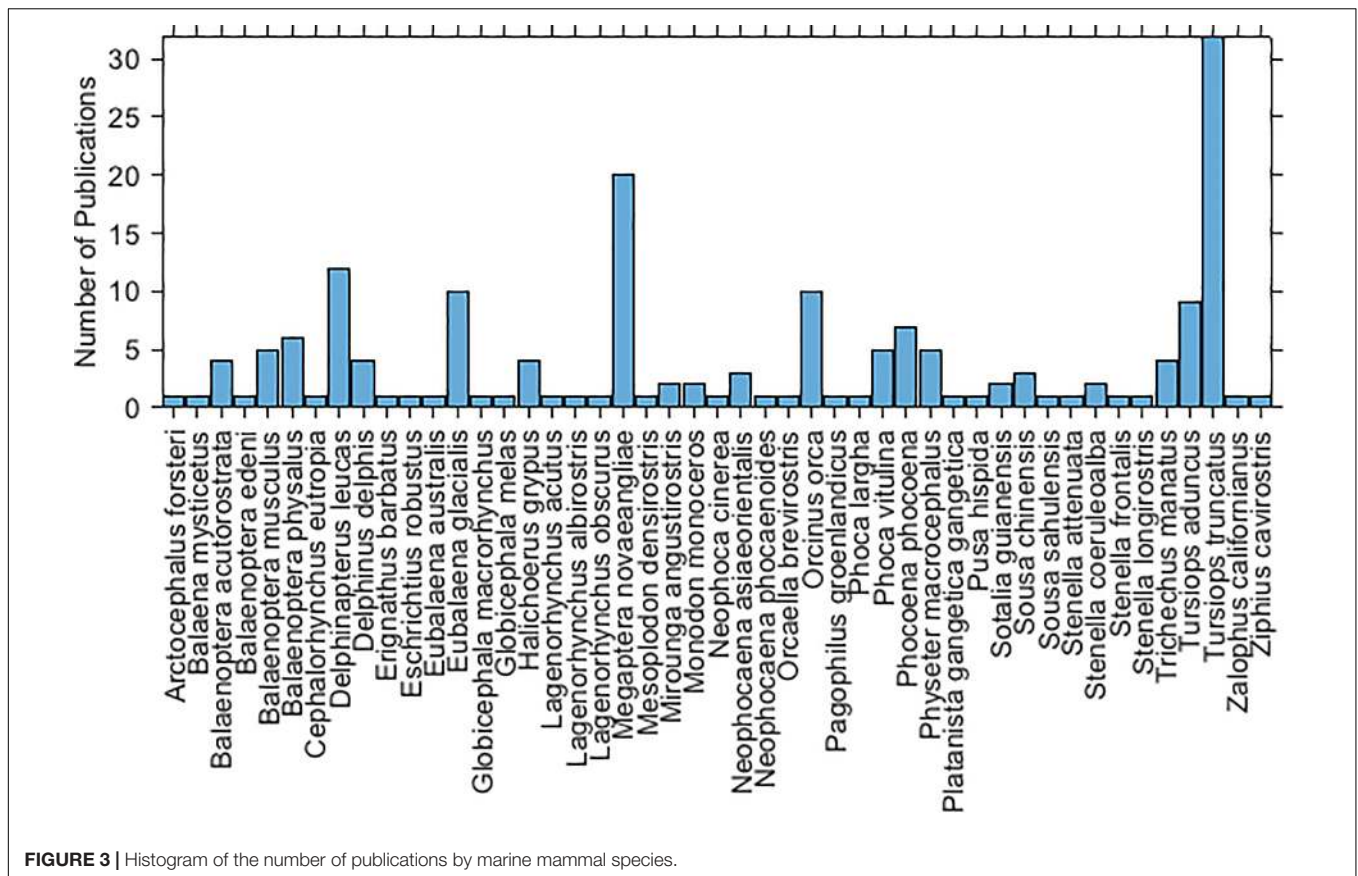


FIGURE 3 | Histogram of the number of publications by marine mammal species.

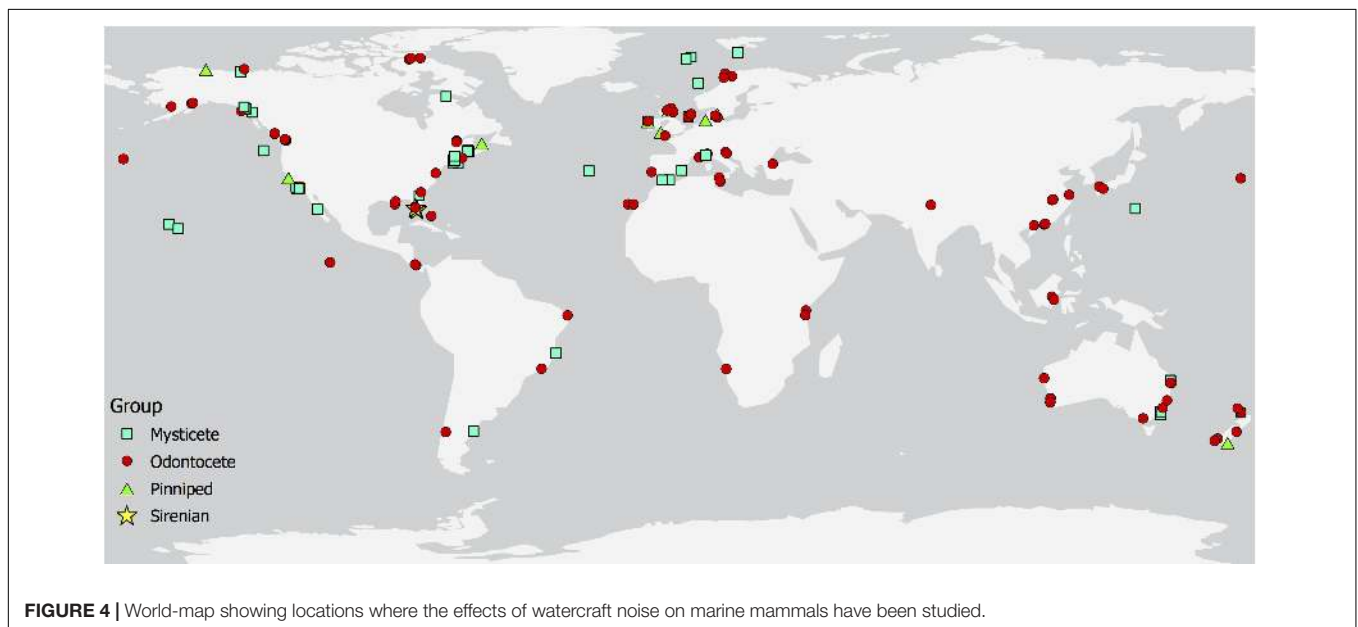


FIGURE 4 | World-map showing locations where the effects of watercraft noise on marine mammals have been studied.

The reported effects of boat or ship noise on marine mammals include changes in both physical and acoustic behavior, masking of communication and echolocation sounds, and stress.

Supplementary Table S1 lists the articles we reviewed and provides information on the following: the types of vessels and marine mammal species studied; the study location, objectives,

design, and methodology; and the animal responses observed or modeled. Several interesting patterns are revealed, which are presented in the following sections, along with discussions of the key findings for particular species groups. Additionally, a number of common issues and problems are identified, which highlight research needs.

Mysticetes

In the early 1980s, concern about the effects of shipping and hydrocarbon development in the Arctic led to several multi-year studies on underwater noise effects on bowhead whales (*Balaena mysticetus*; e.g., Richardson et al., 1982; Greene, 1985; Richardson et al., 1985; Johnson et al., 1986). In these studies, experimental approaches of bowhead whales by small vessels at high speed showed that whales generally moved away, thereby interrupting foraging, socializing, and playing behavior, while spending less time at the surface. The early 1980s also saw the first and only playback experiment on the response to vessel noise by gray whales (*Eschrichtius robustus*) in their breeding and nursery habitat off Mexico (Dahlheim, 1987; Dahlheim and Castellote, 2016). Gray whales have a limited repertoire of low-frequency (40–4000 Hz) vocalizations, overlapping with watercraft noise (Dahlheim et al., 1984; Moore and Ljungblad, 1984; Dahlheim and Castellote, 2016; Burnham et al., 2018). In the presence of ships and boats, gray whales increased their vocalization rate, and at times of increased outboard engine noise, received levels from gray whales were higher (interpreted as an increase in source levels; Dahlheim, 1987; Dahlheim and Castellote, 2016).

An increase in studies on the potential effects of vessel noise on a wider range of mysticete species has occurred in recent years. The most extensively studied species is the humpback whale. Humpback whales in Glacier Bay National Park, AK, United States of America, are prone to high noise exposures from tourism vessels and have been shown to increase the amplitude of their vocalizations by 0.8 dB for every 1.0 dB increase in ambient noise, while vocalizing less frequently (Frankel and Gabriele, 2017; Fournet et al., 2018). Similarly, singing individuals near Chichi-jima Island ceased their song after a passenger-cargo vessel passed within 1400 m (Tsuji et al., 2018). Humpback whales off the Australian east coast exhibited great variation in behavioral responses to seismic survey vessels with the airguns turned off. While no behavioral change was seen in some trials, others revealed a decrease in dive duration, travel speed, and the number of breaches (Dunlop et al., 2015, 2016, 2017a,b, 2018). Most humpback whales did not respond to sonar vessels with the sonar turned off (Sivle et al., 2016; Wensveen et al., 2017). Tsuji et al. (2018) found that humpback whales moved away from large vessels, while others noted changes in respiratory behavior (Baker and Herman, 1989; Frankel and Clark, 2002) and a cessation of foraging activities (Blair et al., 2016). The large number of studies on humpback whales and the resulting variety of documented responses demonstrate that context affects behavior.

Conversely, North Atlantic right whales (*Eubalaena glacialis*) show no behavioral response to ship noise at all, or at least not to received levels of 132–142 dB re 1 μ Pa rms from large ships passing within 1 nm distance, nor to received levels of 129–139 dB re 1 μ Pa rms (main energy between 50 and 500 Hz) from ship noise playback (Nowacek D.P. et al., 2004). A lack of behavioral response of right whales to ship noise is particularly concerning due to the high levels of ship strike in this species (Laist et al., 2001), affecting their conservation status (Kraus et al., 2005). Nevertheless, analyses of North Atlantic right whale fecal samples suggested that noise from large commercial vessels might increase stress levels (Rolland et al., 2012). In

addition, studies suggest that right whales have vocally adapted to environments with increased low-frequency noise through a shift in vocalization frequency and duration (Parks et al., 2007a, 2009, 2011), which may have been a response to compensate for a loss in communication range (Clark et al., 2009). Tennessen and Parks (2016) modeled the communication space of mother-calf pair up-calls in the vicinity of container vessels and found that an up-call would only be detected when the receiving whale was 25 km from the moving vessel and within 320 m of the transmitting whale. Another important social call for right whales, the gunshot, was also found susceptible to masking by vessel noise (Cunningham and Mountain, 2014).

A decrease in communication range as a result of increased levels of ship noise has also been modeled for Bryde's (*Balaenoptera edeni*), fin (*Balaenoptera physalus*), humpback, and minke whales (*Balaenoptera acutorostrata*) (Clark et al., 2009; Cholewiak et al., 2018; Gabriele et al., 2018; Putland et al., 2018). The Lombard effect comprises changes in the spectral features of vocalizations (i.e., in frequency and level) and in vocalization rates, in order to compensate for masking (Lombard, 1911). In addition to the examples from gray, humpback, and right whales above, fin whales lowered the bandwidth, peak frequency, and center frequency of their vocalizations under increased levels of background noise from large vessels (Castellote et al., 2012).

Less attention has been paid to the effects of noise generated by smaller vessels. Dunlop (2016b) predicted an increase in humpback whale social call source levels and the proportion of surface-generated sounds under increased vessel noise, as observed in response to increased wind noise. However, no behavioral changes were observed at received levels of 91–124 dB re 1 μ Pa rms from a recreational fishing vessel. Au and Green (2000) studied the response of humpback whales to four different whale-watching vessels, each with their own acoustic signature, approaching to 91 m distance. Individual whales responded strongest (i.e., abrupt changes in direction and longer dive durations) to the vessel with the highest received level (127 dB re 1 μ Pa, 1/3 octave band level at 315 Hz). Several other studies report on the behavioral responses of mysticete whales to smaller vessels in the absence of noise measurements. These studies indicate avoidance of vessels at close range (Palka and Hammond, 2001; Stamation et al., 2010). Changes in behavioral state and respiratory behavior were also observed (Jahoda et al., 2003; Morete et al., 2007), with mother-calf pairs eliciting stronger responses than adults (Morete et al., 2007).

Odontocetes

Much of the significant early work on the potential effects of watercraft noise on odontocetes was—similar to studies on mysticetes—a result of concern about Arctic industrial development (hydrocarbons, mining, and shipping) in the early 1980s (e.g., LGL Ltd., 1986; Finley et al., 1990; Richardson et al., 1990). The focal species were beluga whales and narwhals (*Monodon monoceros*). In response to icebreakers, beluga whales lost pod integrity, commenced rapid movement, asynchronous and shallow dives, and changed their vocal behavior (i.e., vocalization types) at received levels of 94–105 dB re 1 μ Pa rms (20–1000 Hz), while narwhals changed their locomotion (i.e., exhibited more directed and slower movement, became

motionless, and sank) and fell silent at received levels of about 124 dB re 1 μ Pa rms (20–1000 Hz) (LGL Ltd., 1986; Cosens and Dueck, 1988; Finley et al., 1990). Since the 1990s, beluga whale responses to boats and ships have been studied more extensively in the St. Lawrence Estuary, Canada. Here, beluga whales have shown increasing avoidance (i.e., increased dive duration and swim speed) with the number of boats, as well as other changes in both physical and acoustic behavior (Blane and Jaakson, 1994; Lesage et al., 1999). The Lombard effect has been demonstrated as an increase in source level, vocalization rate, and frequency (i.e., shift to higher frequencies; Lesage et al., 1999; Scheifele et al., 2005).

In the case of beaked whales, much effort has been spent on understanding the potential effects of ship-based sonar transmissions given coincident strandings and naval exercises (e.g., DeRuiter et al., 2013; Goldbogen et al., 2013; Sivle et al., 2015; Kvadsheim et al., 2017). The effects of ship noise without sonars have been investigated less. Using passive acoustic monitoring and acoustic tags, ship noise at received levels of approximately 135 dB re 1 μ Pa rms (0.1–45 kHz) affected beaked whale foraging by reducing both the horizontal area in which animals foraged and the number of successful prey captures (as indicated by the number of feeding buzzes recorded), with foraging efficiency reduced by >50% (Aguilar Soto et al., 2006; Pirotta et al., 2012). Similarly, fewer clicks were recorded of sperm whales (*Physeter macrocephalus*) during vessel passes (Azzara et al., 2013), and decreases in surface time, respiration interval, and the number of ventilations were reported in the presence of whale-watching boats (Gordon et al., 1992). A different study found no decrease of sperm whale acoustic detections in ship noise (André et al., 2017). Rather, an increase in sperm whale acoustic and visual detections was found near longline fishing vessels, and propeller cavitation noise (to be exact, changes in that noise corresponding to typical operational changes in longline fishing vessel speeds) was identified as the ‘dinner bell’ attracting sperm whales to depredate (Thode et al., 2007). Such diverse responses (avoidance, no response, and attraction) highlight the importance of context in assessments of underwater noise.

Killer whales (*Orcinus orca*) in British Columbia and Washington State have recently received much attention with regards to impacts from ships, given the steady decline in their population size. Changes in behavior (i.e., less foraging and increased surface-active behavior), respiration, and swim speed and direction occurred at received levels above 130 dB re 1 μ Pa rms (0.01–50 kHz), and the Lombard effect (i.e., increased source level and vocalization duration) has been reported in ship noise levels above 98 dB re 1 μ Pa rms (1–40 kHz) (Foote et al., 2004; Holt et al., 2009, 2011; Lusseau et al., 2009; Noren et al., 2009; Williams et al., 2002, 2014). This geographic area has seen a lot of ship noise recording, quantification, and impact modeling studies (e.g., Erbe, 2002; Erbe et al., 2012, 2014; Williams et al., 2015; Cominelli et al., 2018; Joy et al., 2019).

A great deal of research has also focused upon smaller delphinids. Occupying habitats from freshwater rivers to coastal estuaries and the open ocean, dolphins often experience high habitat overlap with human activities. In particular, the potential

impacts from dolphin-watching tourism vessels have been investigated (e.g., Scarpaci et al., 2000; Lusseau, 2003a, 2005, 2006; Constantine et al., 2004; Lusseau and Higham, 2004; Bejder et al., 2006; Stensland and Berggren, 2007; Arcangeli and Crosti, 2009; Christiansen et al., 2010; Steckenreuter et al., 2012; Guerra et al., 2014; May-Collado and Quinones-Lebron, 2014; Symons et al., 2014; Heiler et al., 2016; Pérez-Jorge et al., 2016). Dolphins were displaced or changed their site occupancy in response to vessel traffic (Lusseau, 2005; Bejder et al., 2006; Rako et al., 2013; Pirotta et al., 2015b; Pérez-Jorge et al., 2016). They altered their movement patterns within an area in response to vessel traffic, with animals changing their direction of travel, beginning to travel erratically, or significantly increasing traveling speeds when approached by vessels (Au and Perryman, 1982; Nowacek et al., 2001; Mattson et al., 2005; Lemon et al., 2006; Lusseau, 2006; Christiansen et al., 2010; Marley et al., 2017b). Watercrafts can cause a shift in dolphin behavioral budgets, generally increasing time spent traveling whilst decreasing time spent resting and socializing (Lusseau, 2003a; Constantine et al., 2004; Stensland and Berggren, 2007; Arcangeli and Crosti, 2009; Steckenreuter et al., 2012; Marley et al., 2017b). Other changes in behavior can include alterations to dive patterns, displays of breathing synchrony, and changes in inter-animal distances (Janik and Thompson, 1996; Nowacek et al., 2001; Hastie et al., 2003; Krieb and Rahadi, 2004; Stensland and Berggren, 2007). Furthermore, dolphins have been observed to alter their whistle characteristics, such as their frequency range, in elevated noise conditions or in the presence of vessels (Morisaka et al., 2005; May-Collado and Wartzok, 2008; Guerra et al., 2014; May-Collado and Quinones-Lebron, 2014; Papale et al., 2015; Heiler et al., 2016; Rako Gospić and Picciulin, 2016; Marley et al., 2017b). Changes to whistle duration have also been reported (May-Collado and Wartzok, 2008; Guerra et al., 2014; May-Collado and Quinones-Lebron, 2014), as have increases in whistle production rates (Scarpaci et al., 2000; Van Parijs and Corkeron, 2001; Buckstaff, 2004; Guerra et al., 2014; Martins et al., 2018).

However, delphinid studies are heavily biased toward particular species, with some receiving considerably more research attention than others. The bottlenose dolphin (*Tursiops* spp.) has been the focus of the most research effort of all the odontocetes. Bottlenose dolphins have a cosmopolitan distribution, ranging from northern Scotland to southern New Zealand and occupying both coastal and pelagic habitats. As a result, they are available to marine mammalogists around the world, and so dominate the literature. Bottlenose dolphins are also the most common cetacean kept in captivity, which has facilitated a range of physiological studies regarding the impacts of noise that have not been possible for other species; e.g., studies on how behavioral and acoustical changes affect energetics. Dolphin metabolic rates increase during periods of vocal effort and sound production, with energy requirements varying according to the type of sound produced (Noren et al., 2013; Holt et al., 2015, 2016). This combined with increased energy expenditure due to more time spent traveling, moving at speed, avoiding vessels, or leaving impacted areas, results in disturbance having potential cumulative energetic consequences.

Conversely, little is known about the responses of dolphin species that inhabit relatively constrained systems that are also some of the world's busiest waterways. The river systems utilized by these species are known to have high levels of vessel traffic and, in some cases, there is evidence of river dolphins being the target of tourism activities (e.g., boto, *Inia geoffrensis*, in Brazil; de Sá Alves et al., 2012). Ganges river dolphins (*Platanista gangetica gangetica*) showed mixed responses to approaching vessels, including changing direction to orient away from the boat, prolonging dive times, and displaying attraction toward the boat, as well as no obvious effect (Bashir et al., 2013). Such variability, again, shows the importance of context in behavioral responses. Finally, there is a clear paucity of publications addressing the responses of river dolphins (Families *Iniidae*, *Platanistidae*, *Pontoporiidae*, and *Lipotidae*) to vessel traffic or noise.

Similarly, of the porpoise species, only harbor porpoises (*Phocoena phocoena*) and finless porpoises (Indo-Pacific, *Neophocaena phocaenoides*; Yangtze, *N. asiaorientalis asiaorientalis*) have been studied with regards to the impact of watercraft. Harbor porpoises moved away from vessels (Palka and Hammond, 2001), showed higher levels of porpoising in the presence of boats (Dyndo et al., 2015), changed behavioral states (Akkaya Bas et al., 2017), reduced foraging behavior (Wisniewska et al., 2018), and experienced decreased communication ranges (Hermannsen et al., 2014). Acoustic tags (DTAGs) placed on harbor porpoises in Danish waters showed that animals encountered vessel noise 17–89% of the time, and exhibited vigorous fluking, bottom diving, interrupted foraging, and cessation of echolocation during some high vessel noise events (received level > 96 dB re 1 μ Pa at 16 kHz 1/3 octave band; Wisniewska et al., 2018). Meanwhile the Yangtze finless porpoise has been shown to forage in busy (port) areas exhibiting high vessel traffic, with no detected impact on echolocation behavior (Dong et al., 2012; Wang et al., 2014). Wang et al. (2015) proposed that the high prey densities in the ports in comparison to surrounding areas mean porpoises need to forage there regardless of boat traffic. The closely related Indo-Pacific finless porpoise appears not to exhibit the same pattern, with echolocation behavior showing a negative correlation with ship traffic (Akamatsu et al., 2008). Porpoises may be more vulnerable to this type of disturbance due to their small size and low fat reserves, such that any disturbance that reduces foraging opportunities may result in negative fitness consequences (Nabe-Nielsen et al., 2014; Wisniewska et al., 2016).

Sirenians

Knowledge about the potential effects of watercraft noise on sirenians grew from curiosity of why these animals did not avoid approaching boats and whether they perhaps could not hear them. Fatal collision with watercraft is a serious problem that has been recognized since the 1970s (Ackerman et al., 1992; O'Shea, 1995; Marsh et al., 2001; Rycyk et al., 2018). The majority of these fatalities are a result of blunt force trauma rather than propeller cuts (Lightsey et al., 2006). Vessel strike is the main source of mortality for some populations (e.g., 25% of all Florida manatee, *Trichechus manatus latirostris*, deaths; Calleson and Kipp Frohlich, 2007). Consequently, an understanding of the

hearing capabilities of sirenians has been of interest to determine the capabilities of sirenians to detect watercraft noise. There are no data for dugong (*Dugong dugon*); however, manatee hearing underwater is sensitive at 1–30 kHz (Klishin et al., 1990; Popov and Supin, 1990; Gerstein et al., 1999; Gaspard et al., 2012). This overlaps with the spectrum of noise from boats, raising the question of why manatees do not manage to avoid a vessel strike. The current hypothesis is that, as they spend a great deal of time very close to the sea surface, received noise levels from watercraft are low due to the Lloyd's mirror effect and less sound radiation toward the bow. This, combined with manatees' relatively low movement speed, leaves manatees vulnerable to vessel strikes (e.g., Gerstein et al., 1999).

Conversely, some behavioral studies have concluded that manatees (*Trichechus* spp.) are able to detect and respond to approaching boats, often changing their orientation (heading or roll), depth, diving behavior, behavioral state, and swimming speed (Nowacek S.M. et al., 2004; Miksis-Olds et al., 2007b; Rycyk et al., 2018). Such responses to vessels were more pronounced for vessels in close proximity and traveling at speed (Nowacek S.M. et al., 2004). Dugongs were also affected by close boat approaches and less likely to continue feeding when vessels traveled within 50 m (Hodgson and Marsh, 2007). Manatees foraged in habitat with lower ambient noise (that included vessel noise below 1 kHz), particularly at times with less boat density (Miksis-Olds et al., 2007a). Playback experiments simulating different boats at different speeds approaching to within 10 m supported earlier behavioral response studies that manatees swam to deeper waters in the presence of boat noise (Miksis-Olds et al., 2007b).

Pinnipeds

Pinnipeds are amphibious and haul out on land or ice to breed, pup, molt, and rest. Consequently, much of the research examining vessel traffic has focused on the easily observable reactions of hauled-out pinnipeds to approaching boats and ships. This includes the haul-out behavior of harbor seals (*Phoca vitulina*) (Andersen et al., 2012; Blundell and Pendleton, 2015), Australian fur seals (*Arctocephalus pusillus doriferus*) (Stafford-Bell et al., 2012), Saimaa ringed seals (*Phoca hispida saimensis*) (Niemi et al., 2013), Australian sea lions (*Neophoca cinerea*) (Osterrieder et al., 2017), and walrus (*Odobenus rosmarus*) (Øren et al., 2018). A small number of studies also extend observations to the water surrounding haul-out sites (Osterrieder et al., 2017). Common reactions of pinnipeds to approaching vessels include flushing off haul-out sites into the sea (Jansen et al., 2010; Andersen et al., 2012; Blundell and Pendleton, 2015), increased alertness (Henry and Hammill, 2001), and head raising (Niemi et al., 2013). However, these studies focused on the reactions of pinnipeds to the presence of a vessel rather than perceived levels of vessel noise. Studies that incorporate in-air noise generation, transmission, and reception are very rare (Tripovich et al., 2012). In-air watercraft noise and the perception of sound in air are notably different from their underwater equivalents (Kastak and Schusterman, 1998). Therefore, the remainder of this section and **Supplementary Table S1** focus on studies investigating the impacts of underwater watercraft noise on pinnipeds.

Underwater noise from watercraft has the potential to mask or alter the communication of pinnipeds. Bagočius (2014) showed that gray seal (*Halichoerus grypus*) vocalizations recorded underwater in captivity overlapped with the noise spectrum of a vehicle/passenger ship. Terhune et al. (1979) reported a decrease in the loudness of underwater harp seal (*Pagophilus groenlandicus*) vocalizations after the presence of a vessel was recorded acoustically near whelping sites in the Gulf of St. Lawrence. This may have reflected a change in seal vocalizations or the movement of seals away from the recording area (Terhune et al., 1979).

Studies on the behavioral responses of pinnipeds to shipping noise have been undertaken at a range of spatial scales. A national-scale assessment of seals and shipping in the United Kingdom showed high rates of co-occurrence between gray seals or harbor seals and shipping traffic within 50 km of the coastline near haul-out sites (Jones et al., 2017). At regional and local scales, it was estimated, using sound propagation models, that harbor seals in the Moray Firth were exposed to 24-h cumulative SEL³ between 170 dB re 1 $\mu\text{Pa}^2\text{s}$ (95% CI 168–172) and 189 dB re 1 $\mu\text{Pa}^2\text{s}$ (95% CI 173–206) from shipping (Jones et al., 2017). When considering the upper limits of the 95% confidence intervals, these predicted values exceeded the estimated thresholds for the onset of TTS (Southall et al., 2007, 2019). Locally in Broadhaven Bay, Ireland, gray seals potentially varied habitat use in response to vessels as indicated by a negative correlation between the numbers of gray seals and construction vessels (Anderwald et al., 2013). A recent study using acoustic tags (DTAGs) that record sound and behavior concurrently showed that harbor and gray seals were exposed to vessel noise 2.2–20.5% of their time at sea (Mikkelsen et al., 2019). In response to vessel noise, a tagged seal changed its diving behavior, switching quickly from a dive ascent to descent (Mikkelsen et al., 2019). This observation agrees with descriptions of changes in diving reported during the development of early acoustic recording tags on juvenile northern elephant seals (*Mirounga angustirostris*) (Fletcher et al., 1996; Burgess et al., 1998). Studies using acoustic recording tags on pinnipeds demonstrate the potential opportunities, and the need, to further explore the impact of shipping noise on the at-sea behavior of pinnipeds.

APPROACHES TO STUDY DESIGN

In order to compare studies, identify focus areas and research gaps, and point out common issues and problems, we defined a ‘study’ as a unique combination of publication reference and species. For example, if a publication dealt with two species, then this was counted as two studies. However, if a publication investigated the same species at two different sites, then this was counted as one study.

With this definition, an approximately equal number of studies dealt with large ships as with small boats (ratio: 1.05:1).

³The sound exposure level (SEL) is a measure of the total noise energy over time. It is computed as the time-integral of the squared pressure, before applying 10 $\log_{10}()$, and it is expressed in dB relative to 1 $\mu\text{Pa}^2\text{s}$ (International Organization for Standardization, 2017).

Animal responses to these vessels were observed in the wild in 82% of studies, while 4% of studies were done in captivity and 14% of studies used models instead of live animals. The majority of studies on live animals dealt with real vessels *in situ*, while 5% were playback studies of pre-recorded sound.

In terms of measuring animal responses, 34% of studies undertook vessel-based observations, 19% land-based observations, and 8% aerial observations. Passive Acoustic Monitoring (PAM) was employed in 33% of studies, and tags were used in 13% of studies. Some studies used more than one method of observation. Studies were designed as controlled exposure experiments (14%) or before-during-after observations (29%), while 21% were opportunistic in nature.

Out of all studies, 28% determined the received noise level at the study animals, 13% measured the received level, 12% used a sound propagation model to determine the received level, and 3% applied a geometric propagation loss. In addition to determining the received level, 15% of studies also considered frequency-dependent hearing sensitivity of the animals (e.g., audiograms or critical bands). A total of 41% of studies neither estimated the received level nor the range of the vessel to the animals.

In terms of context, 58% of studies considered vessel-related factors such as vessel numbers, types, speeds, distances, directions of approach, etc. Environmental factors such as location, habitat type, bathymetry, tide, sea state, temperature, prey presence, and ambient noise (in addition to vessel noise) were considered by 42% of studies. Biological factors such as group demographics, behavioral state, speed of movement etc., were considered by 46% of studies. Only 17% of studies did not consider any contextual variables. However, the majority used only very few and basic contextual variables such as range to the vessel, ambient noise, and current behavioral state.

COMMON ISSUES AND PROBLEMS

With Physics: Estimation of Exposure, Recording, and Playback of Vessel Noise

Studies on the effects of watercraft noise on marine mammals would ideally be able to determine the sound levels received by the animals and the total sound exposure (i.e., the integral of the squared sound pressure over time; International Organization for Standardization, 2017). Few studies employed acoustic recording tags on the animals, which store a record of received levels over time right at the animal. The majority of studies that determined received levels did so by modeling and estimation. In this case, watercrafts are recorded at some site, source levels are estimated, and these estimates are then applied to mostly different situations (i.e., locations, environments, and times of year) for the computation of received levels. There are common problems with all of these steps.

Measuring ship noise is not as simple as lowering a hydrophone over the side of a boat. Over-the-side deployments as well as hydrophones suspended straight from surface buoys may record noise from wave action against the boat or buoy, and show artifacts from the hydrophone moving through the water with the waves, affecting acoustic recordings at frequencies from

a few Hz to a few kHz (e.g., Strasberg, 1979; Cato, 2008; Erbe et al., 2016c). Common in moored deployments, flow noise is an artifact of recording resulting from hydrodynamic flow past the hydrophone, which causes non-acoustic pressure fluctuations at approximately 0.005–1 kHz range (e.g., Buck and Greene, 1980; Erbe et al., 2015). Strong currents might set mooring ropes and legs into vibration and resonance, causing mooring noise at a few hundred Hz to a few kHz (e.g., Koper et al., 2016). Metal chains and shackles in moorings cause clonking noise in the same frequency range (~100 Hz to a few kHz; e.g., Marley et al., 2017a). Many such artifacts can be minimized with hydrophones deployed on the seafloor (e.g., McCauley et al., 2017), though soft seafloor material such as sand moving over the hydrophone may contaminate acoustic recordings up to a few kHz (e.g., Erbe, 2009). Alternatives are arrangements that drift freely with the currents. The recorder is suspended from a buoy via a suspension system, which may comprise a drogue and a bungee that decouple the hydrophone from surface wave action. Similarly, a catenary (or distributed buoyancy) arrangement will decouple the hydrophone and spatially remove it from potential noise generated at the surface buoy (Figure 5). Building noise-free moorings is an art, and different designs may be required for different situations.

An international standard has recently been developed for the measurement of ship noise in deep water (i.e., water depth more than 150 m or $1.5 \times$ ship length, whichever is greater) (International Organization for Standardization, 2016). The ship travels along a pre-defined course, and recordings are taken from both port and starboard aspects. While the standard does not specify a certain speed, it would be good to obtain measurements at multiple speeds representing typical operational speeds. Recording is done in the geometric far field (i.e., closest point of approach 100 m or $1 \times$ ship length, whichever is greater) with a vertical array, having three hydrophones at specified inclination angles from the ship. The 'radiated noise level' (RNL, referenced to 1 m) is computed by applying a geometric (spherical) spreading loss term [$20 \log_{10}(\text{range})$] over the slant range for each hydrophone and then averaging over all hydrophones. This averaging smooths over the Lloyd's mirror interference pattern. The RNL is useful for noise emission studies, but may lead to large errors when used to estimate received levels at animals in other environments. This is because the environment in which the ship was recorded affects RNL. The recent release of Part 2 of this standard (International Organization for Standardization, 2019) provides formulae to estimate equivalent monopole source levels that correct for surface effects.

In order to compute environment-corrected monopole source levels, sound propagation models need to be applied that translate levels recorded at long range to levels normalized to 1 m range. There are a number of sound propagation models to choose from—depending on the environment (e.g., Etter, 2003; Jensen et al., 2011). The resulting source levels can then be inputted into sound propagation models for other environments in order to estimate received levels at the animals (e.g., Erbe et al., 2013; Williams et al., 2014). If a spherical spreading loss term is applied rather than a sound propagation model, then source levels are

commonly under-estimated if the recording hydrophone was at shallow inclinations from the ship. Conversely, if monopole source levels are taken from the literature and a spherical loss is applied, then received levels may be over-estimated, when the receiving animal is at shallow inclinations from the ship. These are likely common problems in the literature. For example, the RNLs (re 1 m) of cargo vessels reported by McKenna et al. (2012) and Veirs et al. (2016) were up to 15 and 25 dB less than the source levels (re 1 m) of Simard et al. (2016), respectively, likely due to an underestimation of propagation loss. This is because of the dipole radiation pattern of a ship and its image source, yielding a propagation loss well above the wrongly, yet commonly applied $20 \log_{10}(\text{range})$ at shallow inclination angles (e.g., Ainslie et al., 2014). Using sound propagation models, Chen et al. (2017) showed that gray seals experienced step changes of up to 20 dB in the received ship noise levels as they dove throughout the water column in the Celtic Sea. This was because of environmental features such as thermoclines, which a geometric propagation loss model cannot account for.

Finally, once recordings of watercraft have been obtained, they are sometimes played back to animals in different environments for response studies. The recorded sound was affected (in frequency and level) by the environment in which the recordings were made and by the recording system. It will likely be broadcast in yet another, different environment, resulting in further affected received spectrum levels. In addition, the speaker used for playback will have a frequency response, which can distort the signal. Ideally, the speaker's frequency response is measured, and the playback signal is digitally filtered with the inverse of the frequency response before the playback study. Furthermore, the underwater speaker used will have a rather different sound radiation (i.e., directivity) pattern from the recorded vessel. Finally, it is impossible to simulate an approaching vessel with a single, moored speaker, because not only the received level changes as a vessel approaches, but also its spectrum and directionality.

With Biology: Experimental Design, Disturbance Differentiation, and Biological Significance

One of the most fundamental aspects of experimental design is ensuring that fair comparisons are made. In many response studies, this requires having some idea of 'normal' animal behavior in the form of a control group, with which treatment groups can then be compared for deviations that could imply disturbance (Johnson and Besselsen, 2002). However, here field-based marine mammal studies typically hit a problem: Despite the advancements of acoustic and visual monitoring techniques over recent decades, many fundamental questions regarding marine mammal behavior remain unanswered. As a result, the scientific community are still trying to determine the realms of normal behavior, hindered by continual new discoveries describing range expansions, diving abilities, hearing capabilities, and so on (e.g., Schorr et al., 2014; Cranford and Krysl, 2015; Accardo et al., 2018). Furthermore, all animals are individuals and the response of any given individual may change based on its current

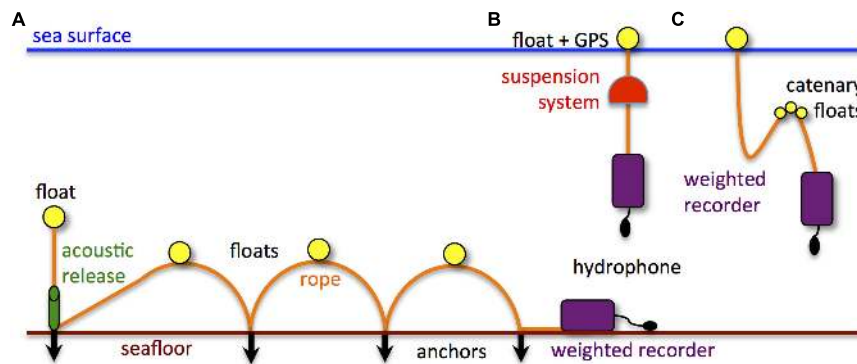


FIGURE 5 | Sketch of hydrophone deployments that minimize mooring artifacts: **(A)** recorder on the seafloor and spatially decoupled from the release mechanism; **(B)** recorder suspended from a surface float via a decoupling suspension system and freely drifting; and **(C)** recorder suspended via a catenary system. The latter could be freely drifting from a surface float or attached to a seafloor anchor.

requirements and motivational states (e.g., health, reproductive status, age, energetic requirements; Pirota et al., 2015a). Overall, this means that within the same species, individuals may respond differently in different environments and at different times, depending upon their previous experience with man-made noise and the importance of the habitat they are occupying for their current life-function requirements. Additionally, as previously discussed, animal behavioral responses can take many forms. This can make it difficult to conclusively identify when disturbance has occurred.

Similarly, a lack of control contexts can further confound results. There are few environments globally which have not experienced anthropogenic stressors (Halpern et al., 2015). Thus, there are few 'naive' populations of marine mammals to serve as baselines in behavioral response studies. This raises the question of habituation (e.g., Cox et al., 2001). Do we see no behavioral response to noise because the population is already used to the presence of such sounds? If so, did behavioral responses ever occur or have animals developed strategies to deal with these noisy environments? And, if such strategies exist, do they evoke an energetic or reproductive cost to the animals involved?

It is possible to account for anthropogenic, biological, and environmental contexts by including a suite of additional variables. In fact, the majority of studies we reviewed tried to account for at least one form of context. Some contextual factors, however, have not been addressed in impact assessments of underwater noise, such as the role of nearby conspecifics (Dunlop, 2016a) or nearby animals of other species (e.g., Koper and Plön, 2016). Contextual data of any type may not always be available or obtainable at a sufficient spatial or temporal resolution to coincide with quick behavioral events (Mannocci et al., 2017). And so, this leads to the issue of sample size. Statistical models with too many variables and insufficient sample size will fail to converge. Consequently, there are minimum sample sizes required for different statistical tests and levels of precision (e.g., Hampton et al., 2019). Unfortunately, the optimum sample size generally cannot be calculated until after the study has been completed. Methods for estimating

it beforehand require some knowledge about variation within the study population (Dell et al., 2002); but, such variation remains poorly understood for the majority of marine mammal species. While increasing the sample size is statistically preferable, the majority of marine mammal studies suffer sample-size restrictions due to logistics and economics.

Once the best possible experimental design has been implemented, there is the problem of disturbance differentiation. Firstly, impact assessment studies are often confounded by the fact that the majority of marine mammal studies are boat-based. This introduces a potential source of observer bias from the presence of the research vessel and the noise it creates. Such bias is unavoidable in many situations, although increasingly researchers are attempting to include this in their analyses (e.g., Lusseau, 2003b). In coastal settings, land-based observations are more readily implementable and may help reduce (or totally exclude) any influence from observer presence. However, this does not assist in resolving the question of whether animals respond to the physical presence of a vessel or if responses are due to the noise that vessel creates, or to any other factor in the environment.

And so, despite the best intentions, many response studies may be restricted to relatively simple analyses, such as the use of basic comparative statistics (such as *t*-tests, ANOVAs, and non-parametric equivalents) to look at one particular behavioral response with and without the presence of ships. This is not to say that such studies are of no value—every result adds another piece to the overall puzzle. But they by no means capture the full context of the situation. Now that long-term datasets are in existence, researchers are increasingly able to apply more complex analytical techniques, consider individual motivations in the study species, and even make predictions using agent- or context-based modeling (e.g., Ellison et al., 2012; Nabe-Nielsen et al., 2014; Pirota et al., 2014).

Once analytical techniques have been applied, the final question is whether any observed response actually matters in terms of biological significance. Behavioral changes associated with anthropogenic activities are often assumed to equate to a

biologically significant effect (New et al., 2013; Curé et al., 2016). Individuals exposed to novel forms or chronic levels of disturbance may be displaced from critical habitat, disrupted from key activities, and thus suffer lower individual fitness, reproductive success, or overall survival (New et al., 2013). However, this may not be the case for infrequent disturbance resulting in instantaneous or short-term responses. For example, although animals may initially leave a site when exposed to anthropogenic activities, this may not equate to their utilizing lower-quality habitats or experiencing long-term, broad-scale displacement (Thompson et al., 2013). Recently, several studies have attempted to investigate biological significance using advanced mathematical models that allow for complexity of animal behavior, motivational state, social structure, and exposure to anthropogenic activities (e.g., New et al., 2013). Unfortunately, ground-truthing the outcomes is logistically challenging, requiring long-term studies at the individual- and population-level. Therefore, most behavioral studies are still restricted to establishing links between short-term measures and long-term population consequences (New et al., 2014).

RESEARCH NEEDS

As can be seen from **Supplementary Table S1**, research on the potential impacts of watercraft on marine mammals has been patchy—in terms of its coverage of species, geographic areas, vessel type, and type of impact. As a result, there are a number of knowledge gaps resulting in several obvious research needs.

Species Coverage

The Society for Marine Mammalogy currently recognizes 126 extant species of cetaceans, pinnipeds and sirenians. While 47 of these species have been studied regarding the impacts of vessel noise, the vast majority have received no attention or at maximum, one publication. More than half (64%) of the mysticete species have at least been the topic of a publication once, as have about half (46%) of the delphinid (Family *Delphinidae*) and half (43%) of the porpoise (Family *Phocoenidae*) species. However, of all the river dolphins (Families *Iniidae*, *Platanistidae*, *Pontoporiidae*, and *Lipotidae*—noting that the latter was declared possibly extinct in 2006), only one publication was found. All of the 22 species of beaked whales (Family *Ziphiidae*) are deep-diving pelagic species and rather cryptic, and so only two have been studied with regard to noise impacts. In terms of sirenians, only the Florida manatee appears in the literature on vessel noise impacts. Out of the pinnipeds, four of 18 phocids (true seals) and one otariid (i.e., eared seals) have been included in publications on responses to vessel noise at sea. Note that we did not review publications on the potential effects of approaching vessels on hauled-out pinnipeds, as underwater noise would not have been the cause.

The most-commonly studied species identified in this review were bottlenose dolphins and humpback whales. Ease of access might have played a role, as these species are widespread and at times exceptionally coastal. Thus their popularity as a target species for vessel noise impact studies does not necessarily reflect

their being a research priority, although many populations do inarguably experience high levels of vessel traffic and noise. In comparison, given that river dolphins experience a multitude of anthropogenic stressors, including often-chronic noise from boats, it is perhaps surprising that these species have not had greater research focus. Rivers are among the most threatened ecosystems in the world (Tockner et al., 2010); but these systems represent problematic study sites for cetacean research. For example, the Indus River dolphin (*Platanista gangetica minor*) historically occurred in approximately 3,400 km of the Indus River and its tributaries; surveying this extensive, narrow and convoluted system is logistically challenging (Braulik, 2006; Jensen et al., 2013). Finding river dolphins and tracking them during response studies is difficult. The literature thus far has consequently focused on abundance estimates and status assessments, as well as documenting and mitigating immediately lethal threats (e.g., bycatch; Smith and Smith, 1998), as opposed to potentially less-obvious threats such as disturbance from vessels and noise. Similarly, the potential impacts on cryptic species like deep-diving, pelagic beaked whales are perhaps not always apparent or easy to study. But impacts could be biologically significant, given the sheer volume and density of ocean traffic, coupled with a vertically downward focused sound radiation pattern and a deep-ocean sound propagation environment that enables very long propagation distances.

Non-cetacean species received considerably less research attention. Sirenians are predominantly found in coastal areas, whereas pinnipeds are tied to land; both these characteristics mean these animals inevitably have high habitat overlap with human activities. Yet the impacts of those activities in terms of their physical presence and associated noise remain poorly understood.

Geographic Area

Another group of species that has been under-represented are those utilizing Antarctic waters. Annually migrating mysticetes critically depend on the Antarctic Ocean in the austral summer for feeding, as they do not feed while on their tropical breeding grounds in the austral winter. Some of the phocid species are truly Antarctic in the sense that they are present there all year round. Antarctica is predominantly governed by high-income countries, and thus might be expected to receive higher levels of research attention. Ship noise, in particular, is rapidly increasing off Antarctica due to booming tourism and heightened fisheries effort (Erbe et al., 2019). While Arctic marine mammals were first studied several decades ago, at a time when industrial development (i.e., mostly offshore oil and gas) was expected to grow rapidly, no such impetus has yielded a research increase in Antarctica. In fact, not a single publication has addressed the potential effects of watercraft noise on marine mammals in Antarctic waters, perhaps because of an absence of oil and gas exploration (as prohibited under the Antarctic Treaty) and the associated funding that accompanies such work. However, the expanding tourism and fishing industries may offer opportunities for future research work.

Not all areas have such opportunities. Marine mammal conservation at a global scale is challenged by a lack of basic

information on species presence, but this is particularly true in the developing world (Braulik et al., 2018). For instance, as noted above, river ecosystems have received relatively little research attention. However, in addition to being logistically challenging study areas, those utilized by river dolphins are all located in developing countries, and so local researchers also experience considerable socio-economic challenges when conducting even baseline research. Overall, the majority of publications identified in this review originated from developed countries. Although this likely in part reflects funding or resource availability, it could also reflect publishing practices. For example, in this review only English-publishing journals were included. Furthermore, whilst studies may have taken place on the impacts of noise on marine mammals in developing countries, this research may not have reached the international, peer-reviewed publication stage. It is likely that this information is available, but difficult to access or not publically available (e.g., internal reports, environmental impact assessments, or local conservation and management plans). Therefore, there is a need not only for greater research in particular geographic areas, but also for sharing of research outcomes with a global audience.

Vessel Type

Vessels ranging from small, rigid-hulled inflatable whale-watching boats to large, powerful icebreakers have been investigated with regards to their potential impacts on certain species of marine mammal. Some combinations of vessel type and marine mammal species are more common than others in the literature. For example, the effects of cetacean-watching tourism vessels have most commonly been studied on bottlenose dolphins, then killer whales, humpback whales, and beluga whales. As tourism vessels are directly targeting marine mammals, it is reasonable to be concerned about the impacts these may have on the animals of interest. This is particularly true in areas where multiple trips occur each day or multiple tourism vessels are in operation, as this could lead to cumulative exposure and impacts. Additionally, cetacean-tourism vessels can also act as platforms of opportunity, allowing researchers the chance to study these animals from the tourism vessel itself rather than a dedicated research vessel. However, whilst there are many studies investigating the impacts of cetacean tourism, few specifically consider noise from tourism vessels.

In comparison, small recreational watercraft, such as jetskis, have received relatively little attention. Recreational watercraft may also have cumulative impacts on marine mammals, with an individual animal potentially encountering a multitude of vessels each day. Personal watercraft are considerably more challenging to document than tour vessels, but, given the continual increase in personal watercraft ownership, these vessels are of increasing concern with regards to noise impacts on marine mammals.

Type of Impact

The types of noise impacts that have been studied are as patchy as the coverage of species, areas, and vessels. Risk assessments are often based on the assumption that affected animals will leave the area. However, as summarized above, there is overwhelming evidence that marine mammals can display a wide range of behavioral responses, ranging from the obvious

(e.g., area avoidance) to the subtle (e.g., shifts in acoustic behavior or raised cortisol levels). Measuring these responses comes with a number of logistical challenges; consequently, many studies have historically focused on the former, easier-to-identify response types. Recent technological developments have facilitated a rise in the number of studies targeting subtler types of impact, which will undoubtedly continue over coming years. However, there is still a need for integrative studies that simultaneously consider multiple response types in order to capture the variation associated with different species, populations, cohorts, and individuals.

One obvious pattern is that the effects of noise on the vocalizations of dolphins have been studied more than on those of other marine mammals. Perhaps this is due to the ease at which coastal dolphins can be recorded these days and due to the stereotypical nature of their vocalizations. This does not imply that acoustic communication is more important (and hence of more concern) in dolphins than other species. In fact, a range of responses can be evidence of disturbance, and more studies simultaneously looking at both physical and acoustical behavior are needed.

A significant gap in our knowledge is our lack of understanding of the potential long-term and population-level impacts and the corresponding biological significance. It could be argued that if a response does not equate to having biological significance, then it is of least concern; such conclusions would have obvious regulatory and management implications, but require considerable ground-truthing. This emphasizes the need for long-term, broad-scale studies targeting a range of response types to examine their consequences at the individual and population level. Physical and vocal behavioral changes impact an individual's energetic costs (Noren et al., 2013; Holt et al., 2015, 2016; Williams et al., 2017), but knowledge on how these costs affect other biologically important functions (e.g., growth and reproduction) is currently absent. Even if population consequences could be ascertained, the question remains how these consequences affect the structure, function, and stability of the ecosystem of which the population is a part (Wong and Candolin, 2015). Recent research has focused on developing a framework for assessing the population consequences of disturbance (PCoD) using sparsely available data, supplementing it with expert elicitation to link changes in individual behavior or physiology to vital rates, and incorporating these into stochastic population models (King et al., 2015; Harwood et al., 2016). This methodology has the benefit of being able to model population consequences on the best available data, identifying gaps in understanding to focus research efforts, and being able to be updated as more data becomes available.

DISCUSSION

The potential for watercraft noise to impact marine mammals is considerable. Some interactions have received particular attention, such as small boats affecting coastal dolphins; cetacean-watching boats affecting the specific populations of whales, dolphins, and porpoises that they target; large commercial ships affecting threatened species such as gray and southern

resident killer whales; and icebreakers affecting Arctic mysticetes and odontocetes. Reasons for these specific combinations of vessel type and species include spatio-temporal overlap in presence, identified research needs (such as an expected rise in industrialization of the Arctic due to climate change), conservation urgency (as in the case of the southern resident killer whale), and ease of access (such as coastal and tourism-targeted species).

Other patterns, in addition to specific species-vessel combinations, emerge. For example, research looking at the effects of small vessels is primarily related to vessel behavior without mentioning noise produced by these vessels. This is in contrast to larger vessels, where the noise factor is more often taken into account. Overall, our understanding of the potential effects of watercraft noise on marine mammals exhibits a number of 'holes.'

In this article, we have summarized the information available in the literature, highlighted some of the data gaps, and identified common problems. Standards are needed for both physical and biological aspects of study design, data collection (including recording of vessel noise and animal responses), data analysis, modeling, and reporting to avoid common mistakes and make results comparable and synthesizable (Erbe et al., 2016a). Given the interdisciplinary nature of the field of noise impacts on marine fauna, multi-disciplinary teams are needed to ensure consistent quality of outcomes.

While this article focused on the impacts of ship noise on marine mammals, ship noise also impacts other marine fauna such as fish (e.g., Slabbekoorn et al., 2010; Simpson et al., 2016) and crustaceans (e.g., Wale et al., 2013). The potential bioacoustic impacts on these species have been of concern for as long as those on marine mammals (Myrberg, 1978). However, despite the longevity of these concerns, there remains an information paucity for many species, populations, and cohorts in terms of the impacts of noise, responses invoked, and biological significance of disturbance. As well as being a concern in its own right, this topic also has biological significance for marine mammals in terms of impacts on their prey species.

Overall, ship traffic is expected to keep increasing by approximately 4% per year over the coming five years, with different rates predicted for different ship types (United Nations Conference on Trade and Development [UNCTAD], 2018). Ship noise is a loss in energy, and vibrating propellers, appendages, and cavities are a structural risk; therefore, there is a natural incentive for the shipping industry to maintain its vessels and thus reduce noise (Leaper and Renilson, 2012; Leaper et al., 2014). Reducing ship noise for environmental reasons has also been on the agenda of the International Maritime Organization (IMO) publishing guidelines on quieting technologies and methods for newly built,

as well as existing, vessels (International Maritime Organization [IMO], 2014). Particularly quiet vessels have been designed for defense and research applications, demonstrating that significant reductions in a ship's noise footprint are achievable (Mitson, 1995; Fischer and Brown, 2005; Bahtiarian and Fischer, 2006; De Robertis et al., 2013; Palomo et al., 2014). The conundrum remains though, whether quieter vessels pose a higher risk of collision with marine mammals.

CONCLUSION

The impacts of ship noise on marine mammals continue to be of great concern. Despite this and increasing research attention over recent years, a number of common problems exist in terms of both the physics and biology of this inter-disciplinary issue. Consequently, a number of knowledge gaps remain. However, growing awareness, improving technology, increasing availability of multi-variate data streams, and analytical advancements have started to provide much-needed context for impact assessments. The continuing growth of long-term data sets is enabling much-needed assessments of chronic exposures at the individual and population level of marine mammals. As a scientific community, we should endeavor to address the gaps highlighted in this review to strategically target under-represented species, geographic areas, vessel types, and types of impact.

AUTHOR CONTRIBUTIONS

CE conceived, designed, and led the study, collected and analyzed the data, prepared the figures and table, authored and reviewed the drafts of the manuscript, and approved the final manuscript. SM and RS contributed to the design of the study, collected the data, prepared the figures, authored and reviewed the drafts of the manuscript, and approved the final manuscript. JS, LT, and CE collected the data, authored and reviewed the drafts of the manuscript, and approved the final manuscript.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fmars.2019.00606/full#supplementary-material>

TABLE S1 | Publications on the effects of ship noise on marine mammals: Reference, vessel type, species, study location, latitude, longitude, study objectives, study design, range to vessel, types of responses, received level, anthropogenic covariates, environmental covariates, biological covariates, and sample size.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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