Received: 7 September 2017 | Accepted: 8 November 2017
DOI: 10.1111/gcb.13996

PRIMARY RESEARCH ARTICLE

WILEY Global Change Biology

Vessel noise cuts down communication space for vocalizing fish and marine mammals

Rosalyn L. Putland[1] | Nathan D. Merchant[2] | Adrian Farcas[2] | Craig A. Radford[1]

[1]Leigh Marine Laboratory, Institute of Marine Science, University of Auckland, Warkworth, New Zealand

[2]Centre for Environment, Fisheries and Aquaculture Science, Lowestoft, Suffolk, UK

Correspondence
Rosalyn L. Putland, Leigh Marine Laboratory, Institute of Marine Science, University of Auckland, Warkworth, New Zealand.
Email: rput037@aucklanduni.ac.nz

Funding information
Royal Society of New Zealand, Grant/Award Number: RDF-UOA1302

Abstract

Anthropogenic noise across the world's oceans threatens the ability of vocalizing marine species to communicate. Some species vocalize at key life stages or whilst foraging, and disruption to the acoustic habitat at these times could lead to adverse consequences at the population level. To investigate the risk of these impacts, we investigated the effect of vessel noise on the communication space of the Bryde's whale *Balaenoptera edeni*, an endangered species which vocalizes at low frequencies, and bigeye *Pempheris adspersa*, a nocturnal fish species which uses contact calls to maintain group cohesion while foraging. By combining long-term acoustic monitoring data with AIS vessel-tracking data and acoustic propagation modelling, the impact of vessel noise on their communication space was determined. Routine vessel passages cut down communication space by up to 61.5% for bigeyes and 87.4% for Bryde's whales. This influence of vessel noise on communication space exceeded natural variability for between 3.9 and 18.9% of the monitoring period. Additionally, during the closest point of approach of a large commercial vessel, <10 km from the listening station, the communication space of both species was reduced by a maximum of 99% compared to the ambient soundscape. These results suggest that vessel noise reduces communication space beyond the evolutionary context of these species and may have chronic effects on these populations. To combat this risk, we propose the application or extension of ship speed restrictions in ecologically significant areas, since our results indicate a reduction in sound source levels for vessels transiting at lower speeds.

KEYWORDS
acoustics, Anthropogenic noise, Automatic Identification System, *Balaenoptera edeni*, bigeye, Bryde's whale, communication space, *Pempheris adspersa*

1 | INTRODUCTION

Anthropogenic activity is changing the soundscape dynamics of many terrestrial and aquatic ecosystems globally (Barber, Crooks, & Fristrup, 2010; Erbe, Williams, Sandilands, & Ashe, 2014; Francis, Ortega, & Cruz, 2009; Frisk, 2012; Hildebrand, 2009; Merchant et al., 2016; Proppe, Sturdy, & St. Clair, 2013). Soundscape ecologists and governing bodies alike are concerned because large commercial vessel noise lies between 0.1 and 1 kHz (Hildebrand, 2009), which overlap the frequency range used by many species of aquatic animals for communication. Invertebrates produce sound both actively for behavioural display (Buscaino et al., 2012) and passively while feeding (Radford, Jeffs, Tindle, & Montgomery, 2008b). Fish typically produce sound for social cohesion (van Oosterom, Montgomery, Jeffs, & Radford, 2016), reproductive displays and territorial defence (Amorim, Vasconcelos, Marques, & Almada, 2006). Similarly, marine mammals use sound as a primary means of communication as well as to attract mates from a great distance (Payne & McVay, 1971; Payne & Webb, 1971). The growing understanding that sound plays a critical role in the life history of many aquatic animals has led to the recognition of anthropogenic noise as a major pollutant of international concern (Richardson, Greene, Malme, & Thomson, 1995; Radford, Kerridge, & Simpson, 2014), with progressively more research programmes around the globe focusing on the effect of noise on aquatic life (Erbe, 2012). Government departments in many countries regulate underwater noise emission, and industries undertake environmental impact assessments before any planned aquatic activity.

Anthropogenic noise can cause effects at scales ranging from individual organisms to ecological communities. At the individual level, anthropogenic noise can cause physical injury and behavioural effects. Physical injury to the vestibular, reproductive or nervous systems, although potentially lethal, is rare (Erbe, 2012) and the injured animal would have to be very close to the noise source for physical damage to tissues and organs to occur (Dooling, Westm, & Leek, 2009). Auditory injury, such as hearing loss or threshold loss depends on the noise level, rise time, duration and spectral characteristics of the introduced signal (Erbe, 2012). The range over which auditory injury can occur is also source dependent (Dooling et al., 2009). Temporary threshold shift (TTS) occurs when the hair cells of the inner ear are fatigued, yielding an increase in the auditory threshold. Fish (Caiger, Montgomery, & Radford, 2012; Smith, Kane, & Popper, 2004) and marine mammal species (Kastak, Southall, Schusterman, & Kastak, 2005; Lucke, Siebert, Lepper, & Blanchet, 2009; Nachtigall, Supin, Pawloski, & Au, 2004) have been found to sustain TTS when exposed to anthropogenic noise. Goldfish (*Carassius auratus*) took 14 days to fully recover to control hearing levels after exposure to 21 days of aquaculture noise (Smith et al., 2004). Mean threshold shifts ranged from 2.9 to 12.2 dB when three species of pinnipeds where exposed to noise, with full recovery of auditory sensitivity occurring within 24 hr (Kastak et al., 2005). The likelihood of TTS occurring is increased the higher the sound level and the longer the duration of exposure (Weilgart, 2007). Permanent threshold shift (PTS) occurs when the hearing does not fully return to normal after noise exposure, for example snapper (*Pagrus auratus*) exposed to airgun noise sustained extensive damage to their hair cells, with no evidence of repair up to 58 days after exposure (McCauley, Fewtrell, & Popper, 2003). However, potentially longer term and large-scale impacts of anthropogenic noise may be on behaviour, including acoustic communication because this can be affected by lower sound intensities (Radford et al., 2014). Introduced sound into an environment could potentially distract or detrimentally change behavioural performance (Purser & Radford, 2011). Furthermore, aquatic animals could be displaced or elect to avoid their habitat permanently in response to introduced sound. Grey whales (*Eschrichtius robustus*) altered their migration course when exposed to low-frequency (160–330 Hz) vessel noise (Moore & Clarke, 2002) and catch rates of cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*) (Engås, Løkkeborg, Ona, & Soldal, 1996) and rockfish (*Sebastes* spp.) (Skalski, Pearson, & Malme, 1992) were lower in habitats following exposure to seismic exploration noise. Alterations in the way conspecifics are distributed in the environment, even for a short time period, could subsequently impact the likelihood of detecting signals and the effort needed to acquire that information. Therefore, exposure to anthropogenic noise could influence not just individual fitness but information flow through conspecific networks and whole communities (Francis & Barber, 2013; Naguib, 2013).

Masking of sound can either be energetic, whereby the signal of interest is overlapped by sound in the same frequency and time, or informational, whereby the signal cannot be disentangled from the ambient soundscape (Clark et al., 2009). Both result in reduction of a caller's communication space (the range over which one conspecific can detect another), as the signal cannot be perceived, recognized or decoded. Anthropogenic noise could significantly reduce the communication space of many aquatic species. Vessel traffic noise reduced the communication range of cod and haddock, which was suggested to affect reproductive success (Stanley, Van Parijs, & Hatch, 2017). The two species vocalize during spawning and potential masking could result in the incorrect assessment of the quality of potential mates and reduction in the ability to attract mates (Rowe, Hutchings, Skjæraasen, & Bezanson, 2008; Stanley et al., 2017). A reduction in the communication space of bottlenose dolphins (*Tursiops truncatus*), because of anthropogenic noise, was suggested to interrupt social behaviour and disrupt group dynamics (Janik, 2000). Furthermore, anthropogenic noise could potentially decrease pup survival by reducing the aerial communication space of female and pup attraction calls for northern elephant seals (*Mirounga angustirostris*; Southall, Schusterman, & Kastak, 2003).

To accurately investigate an animal's communication space, the acoustic behaviour (source level, frequency range and/or hearing threshold) of the animal in question and the local sound propagation conditions must be understood. Habitat type (such as reef, coastal, offshore) and time (whether noise occurs during feeding, breeding or migration) also need to be taken into account to critically assess whether any change is biologically relevant for a particular species (Clark et al., 2009). Uncertainty regarding the specific effects of anthropogenic noise combined with a lack of data on current and historic ambient sound levels limits policymakers in their ability to formulate absolute thresholds for ecologically sustainable sound levels (Merchant et al., 2016). Deep water observations indicate that the ambient soundscape in the Northeast Pacific has been rising by 3–10 dB between 20 and 300 Hz since at least the 1960s (Andrew, Howe, Mercer, & Dzieciuch, 2002), due to increases in the number and gross tonnage of vessels, reflecting global economic growth (Frisk, 2012). Importantly, the extent to which these open ocean trends apply to coastal areas where anthropogenic activity is concentrated is unclear (Merchant, Witt, Blondel, Godley, & Smith, 2012).

A key recommendation of reports dealing with the issue of anthropogenic noise is the need to establish acoustic budgets (Hatch et al., 2008), thereby defining the relative contributions of identifiable sound sources to the soundscape. Acoustic budgets for Stellwagen Bank National Marine Sanctuary, USA (Hatch, Clark, Van Parijs, Frankel, & Ponirakis, 2012; Hatch et al., 2008) and the British Columbia coastline, Canada (Erbe et al., 2014) were among some of the first research efforts to establish baseline data for ecologically significant areas. Understanding the baseline communication space of individual animals is an important step in determining the effect of changes in the acoustic budget of an area. Other studies have focused on determining the key factors contributing to vessel noise, including vessel design, operational and oceanographic characteristics (McKenna, Ross, Wiggins, & Hildebrand, 2012; McKenna, Wiggins, & Hildebrand, 2013). It can be speculated that the communication space of individual animals will undergo the greatest reduction when longer and faster vessel pass by because they have previously been recorded to produce higher source levels (McKenna et al., 2013).

Our study site was the Hauraki Gulf, north-eastern New Zealand, an ecologically significant embayment with numerous species of soniferous marine animals (Putland, Constantine, & Radford, 2017) as well as a major shipping route (Kelly, Sim-Smith, Faire, Pierre, & Hikuroa, 2014), making it a suitable location for the investigation of anthropogenic noise. Defining the relative contribution of vessel noise here in the Hauraki Gulf also provides a bellwether for other coastal port areas because, following global trends, vessel traffic is expected to increase by 70–75% in the next 20 years (Ports of Auckland, 2010). There are also plans in place to accommodate larger vessels as well as increasing container volumes (Auckland Council, 2017; Kaplan & Solomon, 2016). With this in mind, the present study had two objectives: firstly, to establish baseline data on anthropogenic noise from commercial vessels throughout the Hauraki Gulf; secondly, to use this information to determine the effect of vessel noise on the communication space of bigeye, *Pempheris adspersa*, and Bryde's whales, *Balaenoptera edeni*. These two species are both residents of the Hauraki Gulf and communicate using sound (Constantine et al., 2015; van Oosterom et al., 2016; Radford, Ghazali, Jeffs, & Montgomery, 2015). Bryde's whales vocalize at a rate and frequency range similar to many other baleen whales (Moore, Stafford, Dahlheim, & Fox, 1998; Širović, Hildebrand, Wiggins, & Thiele, 2009; Stafford, Mellinger, Moore, & Fox, 2007), suggesting Bryde's whales would be a suitable model species to investigate the potential consequences of increasing anthropogenic noise on vocal baleen whales' communication space in coastal waters. The source level and hearing ability of bigeyes is known from laboratory experiments (Radford et al., 2013, 2015), which can be directly used in the communication space model. Bigeyes also provided the first direct experimental evidence that vocalizations are used as contact calls to maintain group cohesion in fishes (van Oosterom et al., 2016), making communication space directly linked to their life history. It can be speculated that other reef fish vocalize to maintain group cohesion because fishes represent over half of all vertebrate species; therefore, bigeyes are a suitable model species to investigate the effect of anthropogenic noise on the communication space of fishes.

2 | MATERIALS AND METHODS

A passive acoustic monitoring dataset was collected from the study site and analysed to identify recordings that contained the general background soundscape devoid of vessel passage noise (background), and those with vessel passage noise (transient). Automatic Identification Ship tracking data (AIS) was used to single out recordings that contained the closest point of approach (CPA) of vessel passages and the source levels of CPAs were back calculated using a site-specific propagation model. The source level of vocalizations, hearing capability and detection threshold were assessed for each species. The communication space of each species was then quantified according to background, transient and CPA and compared to the baseline communication space (calculated using the median background noise level; Figure S1).

2.1 | Acoustic analysis

2.1.1 | Passive acoustic monitoring

Acoustic data were collected at four listening stations around the Hauraki Gulf, north-eastern New Zealand for 9 months between October 2014 and June 2016 using omnidirectional acoustic recorders (ST202 Ocean Instruments, NZ; Figure 1). Deployment locations

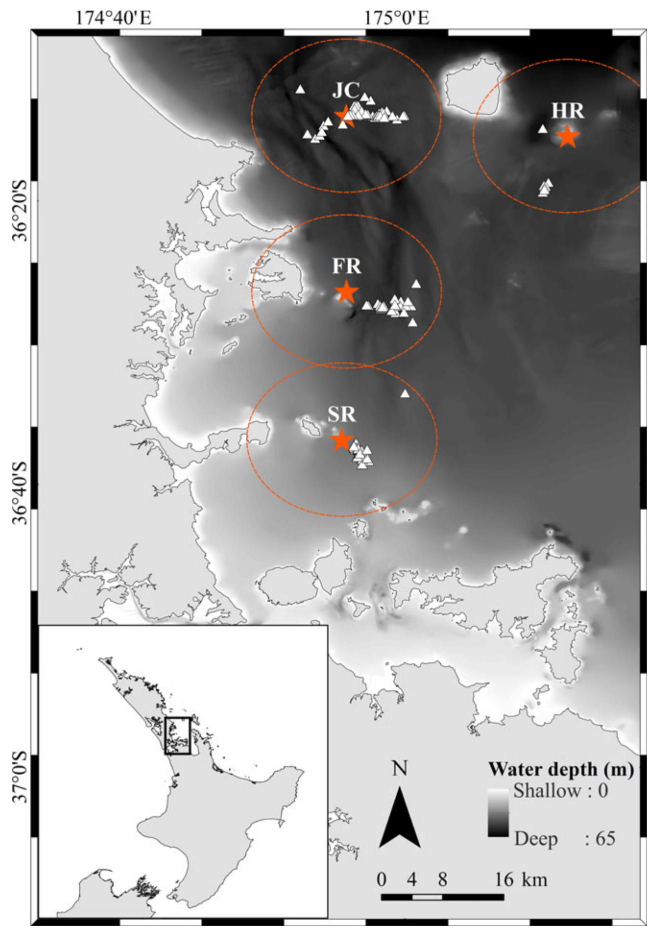

FIGURE 1 Map of the Hauraki Gulf, New Zealand showing the four listening stations: Jellicoe Channel (JC), Flat Rock (FR), Shearer Rock (SR) and Horn Rock (HR) each surrounded by the 10 km radius used to find each vessel's closest point of approach (CPA). Triangles represent the 145 CPAs identified over the 9-month monitoring period. Bathymetry of the area is also shown by the colour-bar from 0 to 65 m. Map produced using ArcGIS 10.3.1 (http://www.esri.com/software/arcgis/)

were chosen to be in close proximity to the most traversed shipping routes into the Ports of Auckland (Constantine et al., 2015). At Horn Rock and Shearer Rock, hydrophones were attached to a weighted stand 1 m off the seafloor and retrieved by a diver. At Flat Rock and Jellicoe Channel, the hydrophones were suspended 2 m off the seafloor using an acoustic release (Desert Star Systems). All hydrophones were calibrated prior deployment using a pistonphone using a 1 kHz tone. At all listening stations, the hydrophones recorded on a duty cycle of 2 min every 20 min for the duration of each deployment, with a sample rate of 144 kHz and −3dB frequency response of 10 Hz–72 kHz. Self-noise of the instruments was <34 dB/√Hz re 1 μ Pa above 2 kHz (Ocean Instruments NZ).

2.1.2 | Adaptive threshold level

Power spectral density (PSD) was calculated in 1 Hz bins (between 10 and 1,000 Hz) for every recording taken during the 9 months of corresponding AIS data using a fast Fourier transformation (FFT), applying a 1 s Hann window with 50% overlap.

An adaptive threshold level (ATL) was then used to determine the relative level of vessel passage noise above the background soundscape (only biological and geophysical sounds). The ATL works on the assumption that the minimum recorded SPL over a given period is representative of *background* sound within that period. The threshold adapts to long-term variations in the broadband SPL while distinguishing short-term relatively high amplitude events as *transient* (Merchant et al., 2012). This method was considered preferable to a fixed threshold, which would be insensitive to the temporal variability of the soundscape (Merchant et al., 2012) and would have to be adjusted for each listening station due to the spatial heterogeneity of soundscapes throughout the Hauraki Gulf (Putland et al., 2017).

The time-dependent ATL(t) for broadband SPLs (10–250 Hz) was calculated as:

$$\mathrm{ATL}(t) = \min[\mathrm{SPL}]_{t-\frac{W}{2}}^{t+\frac{W}{2}} + C(\mathrm{dB\ re\ 1\ \mu Pa}) \tag{1}$$

where ATL(t) is C decibels above the minimum recorded SPL within a rolling time window of duration W centred on time t (Merchant et al., 2012). In this study, W was set to 4 hr, because crepuscular activity on rocky reefs has been found to raise the sound intensity for over 3 hr (Radford, Jeffs, Tindle, & Montgomery, 2008a) and C was set to 9 dB after trialling three different levels (6 dB, 9 dB and 12 dB). The SPL was calculated between 10 and 250 Hz because this was representative of the frequency range of vessel passages.

Once the ATL distinguished background and transient recordings, the concurrent PSD between 10 and 1,000 Hz was retrieved from original PSD calculations.

To verify the ATL was correctly identifying vessel noise as transient, 18 days at each listening station (corresponding to the full and new moon from each month) were manually inspected both aurally and visually using scrolling spectrograms (FFT length = 1,024). At Jellicoe Channel, Flat Rock, Shearer Rock and Horn Rock, the false-positive rate was found to be 0.04, 0.07, 0.04 and 0.11, respectively (Table 1). False positives were caused by rare events that increased the sound intensity between 10 and 250 Hz; at Horn Rock and Shearer Rock the movement of the equipment, at Jellicoe Channel the vocalizations of Bryde's whales and at Flat Rock the sound of earthquakes (Putland et al., 2017).

2.2 | Vessel-tracking data

To further understand the contribution vessel passage sound had on the ambient soundscape, Automatic Identification System (AIS) vessel-tracking data were sourced for the 9 months of acoustic data (November 2014; January, March, April, July, October 2015; and January, February and March 2016). The distance of each vessel from the listening stations was calculated from its AIS latitude and longitude coordinates. Positions were plotted against time, linking data points from the same vessel (identified in the AIS log by the International Maritime Organization (IMO) number). Only vessels classified as container, tanker or cargo passing within a 10 km radius of any listening station were included in this study. Each vessel passage was considered an independent event and vessel identification was not considered as an influencing covariate.

The closest point of approach (CPA) of each vessel (n = 145) was computed geometrically (using great-circle distance), assuming each vessel maintained a direct course and constant speed between AIS transmissions. Each CPA had its concurrent acoustic data manually verified with the CPA eliminated from further analysis if another vessel passed within ±30 min or if an urchin chorus was present (since this would contaminate the subsequent source level estimate at higher frequencies).

2.3 | Source level of vessel passages

Integrating AIS and acoustic data, the received sound level for each CPA was taken as the average PSD from the concurrent 2-min

TABLE 1 Information taken from adaptive threshold (ATL) results. False-positive rate during manual verification. Percentage of recordings over the 9 months analysed that were classified as transient (when broadband sound pressure level (SPL) exceeded ATL) and the median difference in SPL the transient recordings exceeded the concurrent ATL

Listening station	False-positive rate of adaptive threshold level (ATL)	% Transient recordings	Median difference between ATL and transient (±95% confidence) (dB re 1 μPa^2)
Jellicoe Channel (JC)	0.04	18.9	4.9 ± 0.2
Flat Rock (FR)	0.07	7.1	3.1 ± 0.3
Shearer Rock (SR)	0.04	10.2	2.9 ± 0.2
Horn Rock (HR)	0.11	3.9	1.4 ± 0.3

acoustic recording. These received sound levels (RL) were then combined with a model of transmission loss (TL; the sound energy lost along the path from the ship source to the receiver) to estimate the vessel's source level (SL; the root-mean-square sound level of the source at a nominal distance of 1 m, expressed in dB re 1 μPa):

$$SL = RL + TL \tag{2}$$

The transmission loss model was based on Weston's equations (Farcas, Thompson, & Merchant, 2016; Weston, 1971), which accounts for bathymetry and sediment reflectivity characteristics. The original gridded bathymetry data sourced had a resolution of 5–10 m; therefore, a bi-linear interpolation was used to produce a 1 m resolution transect of bathymetry between the listening station and CPA. Seafloor sediment characteristics were obtained from previous sound propagation measurements made in the Hauraki Gulf (Tindle, 1982; Tindle et al., 1978).

Source level estimates were calculated in 1/3 octave bands (American National Standard ANSI, 2004). The SL of CPAs could then be analysed considering speed (kts), gross tonnage and ship length (m) and unique vessels with multiple passages identified.

2.4 | Communication space estimation

Bigeyes vocalize between 74 and 980 Hz (with a source level of 115.8 ± 0.2 dB re 1 μPa at 1 m; Radford et al., 2015) and have a peak hearing sensitivity between 100 and 400 Hz (Radford et al., 2013), which is within the dominant sound energy of their vocalizations. Bryde's whales in the Hauraki Gulf vocalize between 23.5 and 207.8 Hz (Constantine et al., 2015; Putland et al., 2017), with a source level between 152 and 174 dB re 1 μPa at 1 m (Cummings, Thompson, & Ha, 1986; Širović, Bassett, Johnson, Wiggins, & Hildebrand, 2014). As is the case for all baleen whale species, Bryde's whale hearing sensitivity is unknown although it is assumed they are using their vocalizations for interspecific communication, thereby their hearing sensitivity is within their vocalization frequency range.

The communication space of bigeye and Bryde's whales was derived by rearranging the following equation (modified from Clark et al., 2009):

$$SE = SL - TL_{sp} - SPL - DT \tag{3}$$

Where SE is signal excess, which at SE = 0 defines the 50% probability of signal detection; SL is the source level of the vocalization, for bigeyes measured at four frequencies from the third octave bandwidths 125, 250, 500 and 1,000 Hz (Radford et al., 2015) and for Bryde's whales calculated over the frequency range 40–1,000 Hz by averaging data from various sources (Constantine et al., 2015; Cummings et al., 1986; Širović et al., 2014); SPL is the background, transient or CPA SPL; TL_{sp} is spherical spreading transmission loss, calculated as 20log(r) (Mann, 2006), where r is the range in metres, and DT is detection threshold, defined as the difference between the signal and background SPL where a signal can be perceived. There is no data on DT for fish, so a conservative value of 15 dB was used (Kastelein, de Haan, & Verboom, 2007), whereas for marine mammals a widely accepted DT of 10 dB was used (Clark et al., 2009; Kastelein et al., 2007). Furthermore, we assumed for the purpose of these calculations, that (i) signal detection is limited by the ambient soundscape; (ii) vocalization SL does not vary in response to the background SPL and (iii) fish and whales have omnidirectional hearing sensitivity.

The communication space of an individual fish or whale (Equation 4) was derived from Equation 3 when SE = 0,

$$r = 10^{\frac{SL-SPL-DT}{20}} \tag{4}$$

Substituting SPL for three different scenarios:

1. Background received level (to assess how natural variability of the soundscape affects communication space)
2. Transient received level (to assess how routine vessel passages affect communication space)
3. CPA received level (to assess how a vessel passage at a known distance affects communication space).

Each communication space estimate was then compared to a baseline (taken as the median background SPL at each listening station) to standardize the three scenarios (Figures S1 and S2). The difference in communication space was calculated as a unit distance (metres or kilometres) as well as percentage.

3 | RESULTS

3.1 | Detection of vessel passages

The adaptive threshold classified between 3.9 and 18.9% of the recordings from the 4 listening stations as transient suggesting vessel passages (Table 1). As expected, the transient SPL was higher across all third octave frequencies at all listening stations (Figures S3–S6).

3.2 | Impact on communication space

Background SPL decreased communication space for bigeyes (at 250 Hz, the 1/3 octave frequency closest to the vocalization peak frequency) by 42.0, 31.8, 37.7, 27.6% at Jellicoe Channel, Flat Rock, Shearer Rock and Horn Rock, respectively, when compared to the median background SPL. Differences in Bryde's whale communication space followed a similar pattern to that shown for bigeyes. Background SPL decreased communication space (at 40 Hz, 1/3 octave centre frequency closest to peak frequency of the Bryde's whale vocalization) by a maximum of 48.4, 37.2, 44.9 and 25.6% at the four listening stations. Loss of communication space from vessel passages exceeded variability in background sound for both species (Figures 2 and 3). For bigeyes routine vessel passages (identified from transient recordings) decreased communication by 61.5, 55.3, 56.5 and 31.3% at 250 Hz, whilst CPAs decreased the communication space further still by 99.9, 99.8, 99.8 and 99.8% for the four listening stations (Figure 2, Table S1). Likewise, for Bryde's whales

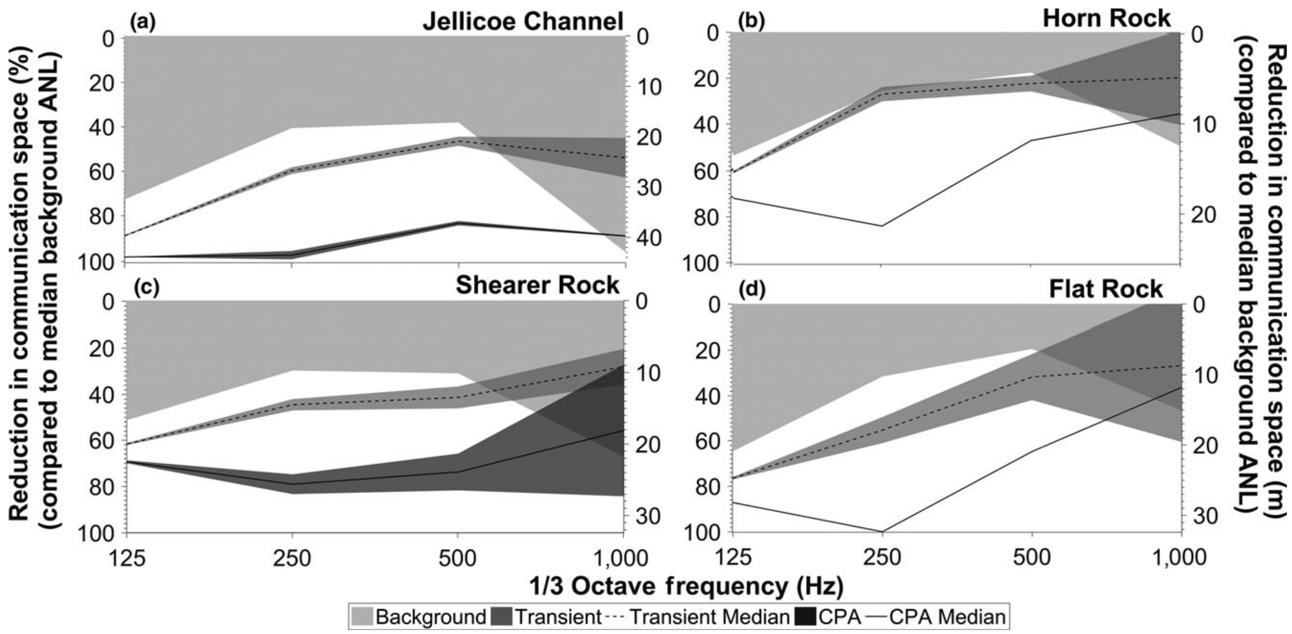

FIGURE 2 Reduction in the communication space (left axis (%) and right axis (metres)) of bigeye caused by the change in the background ANL, transient vessel passages or CPA of a vessel passage. Lines represent the median and shaded areas the 95% confidence intervals

transient vessel passages caused a 84.7, 68.8, 67.3 and 32.7% reduction and CPAs a 99.8, 99.9, 99.9 and 99.9% reduction at the four listening stations (Figure 3, Table S3).

The difference in communication space also differed according to 1/3 octave centre frequency. For bigeyes, the reduction in communication space was highest at 125 and 1,000 Hz (Figure 2), whereas for Bryde's whales, the reduction in communication space was most pronounced in the lower frequencies (40–100 Hz) at Jellicoe Channel, Flat Rock and Horn Rock (Figure 3).

There was also a difference in the effect of sound from background, transient vessel passages and CPA recordings between listening stations, according to the reduction in communication space as a unit distance. However, there was no difference between the listening stations when the reduction is given as a percentage compared to the baseline communication space. Jellicoe Channel had the largest baseline communication space for both species (Figures S2 and S3) reflecting that this station had the lowest median background SPL, at 40 Hz SPL was 76.7 dB re 1 μPa^2/Hz and at 250 Hz

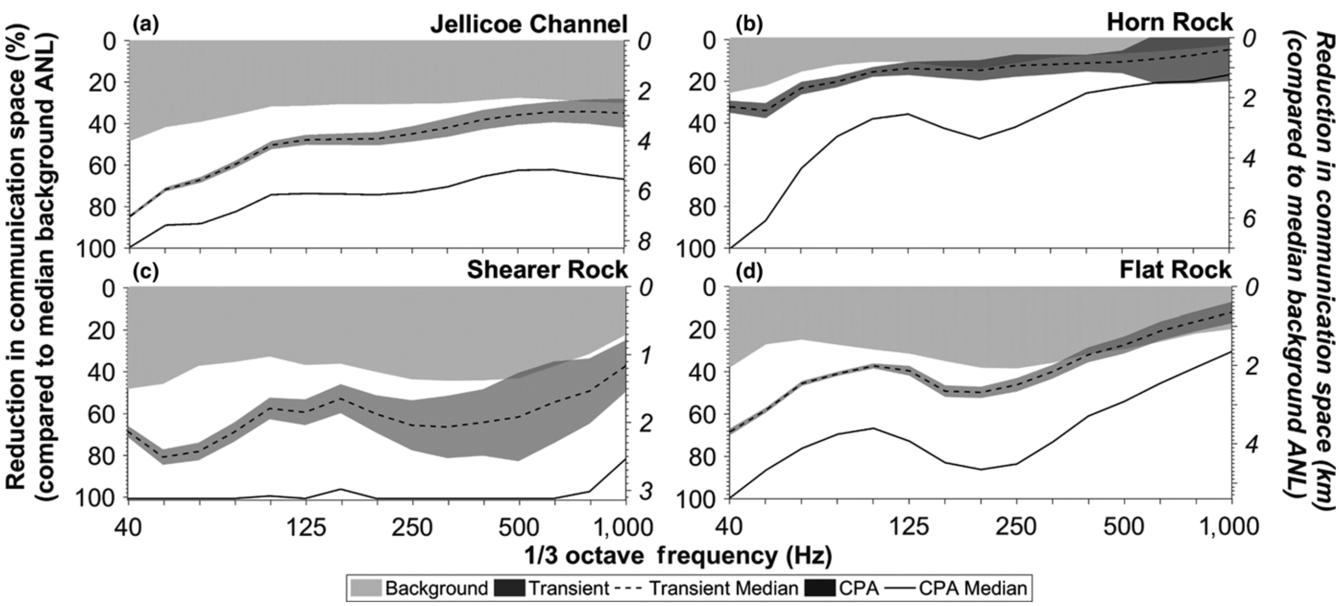

FIGURE 3 Reduction in the communication space (left axis (%) and right axis (metres)) of Bryde's whales caused by the change in the background ANL, transient vessel passages or CPA of a vessel passage. Lines represent the median and shaded areas the 95% confidence intervals

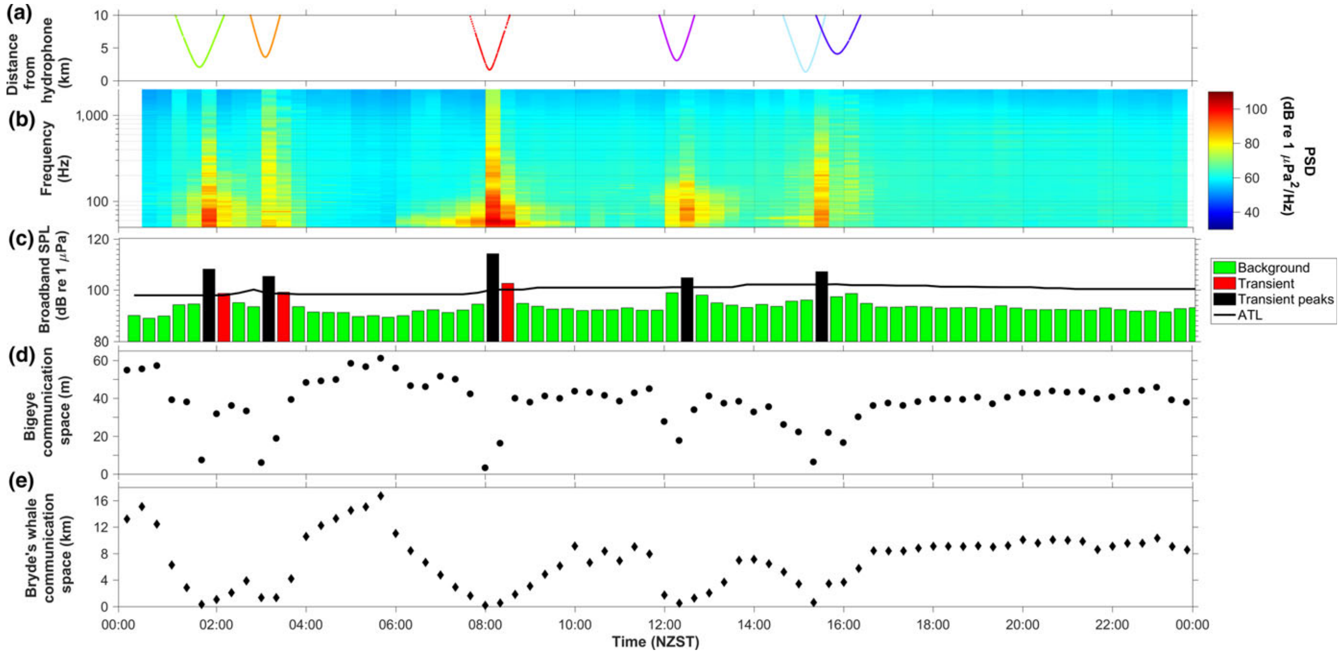

FIGURE 4 Jellicoe Channel 14/07/2015 AIS and acoustic communication information (a) AIS approach of different vessels in different colours. (b) Concurrent power spectral density (dB re 1 μPa^2/Hz) of the received sound level (c) Broadband sound pressure level (SPL) (10–250 Hz) with background and transient represented throughout the day (d) Communication space of bigeye (m) according to the received sound level throughout the day (e) Communication space of Bryde's whales (km) according to the received sound level throughout the day

SPL was 79.3 dB re 1 μPa^2/Hz (Figure S4). Horn Rock and Shearer Rock had the smallest baseline communication space for bigeyes and Bryde's whales, respectively (Figures S2 and S3). At Horn Rock, the SPL was 85.5 dB re 1 μPa^2/Hz at 250 Hz, and at Shearer Rock the SPL was 87.5 dB re 1 μPa^2/Hz at 40 Hz.

3.3 | Temporal effect of vessel passages

Examples of 24-hr periods at Jellicoe Channel and Horn Rock (Figures 4 and 5) demonstrate how the effect of vessel noise on communication space varies with the distance of a vessel from the

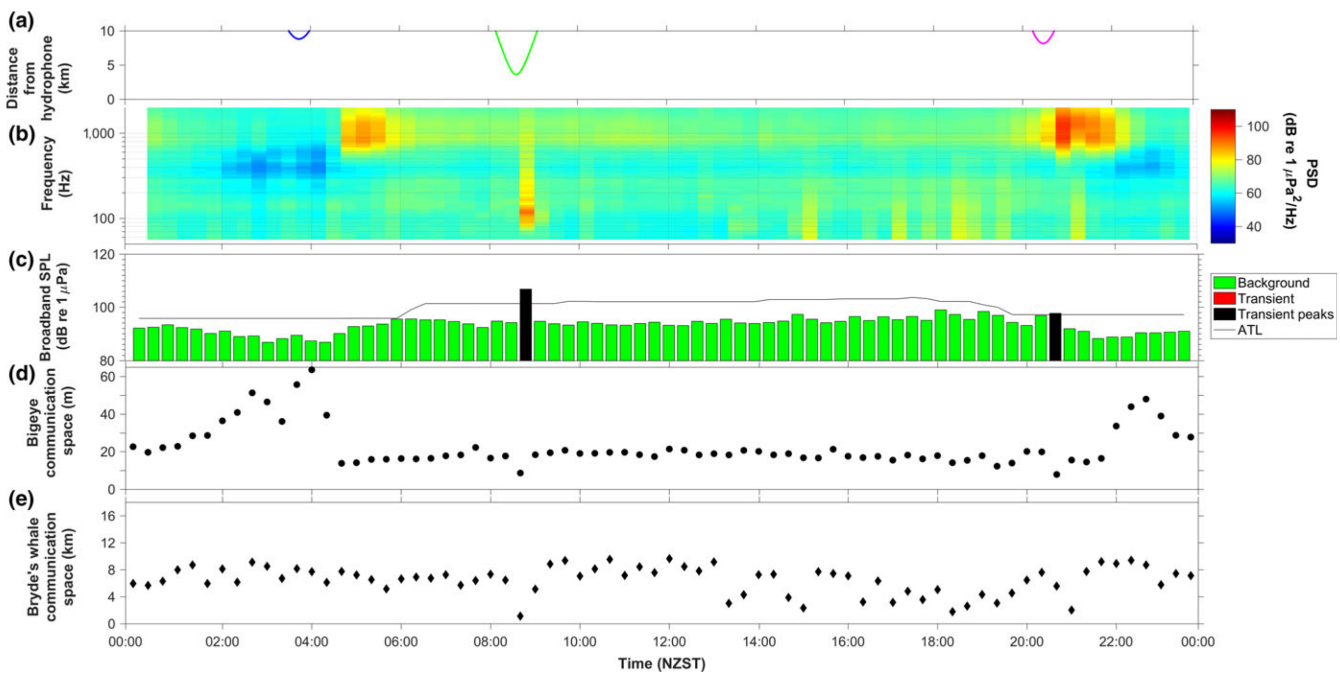

FIGURE 5 Horn Rock 25/11/2014 AIS and acoustic communication information. (a) AIS approach of different vessels in different colours. (b) Concurrent power spectral density (dB re 1 μPa^2/Hz) of the received sound level (c) Broadband sound pressure level (SPL) (10–250 Hz) with background and transient represented throughout the day (d) Communication space of bigeye (m) according to the received sound level throughout the day (e) Communication space of Bryde's whales (km) according to the received sound level throughout the day

listening station. Six separate cargo and container vessels (between 180–221 m and 22,204–60,975 gross tonnes) passed Jellicoe Channel during the 24-hr period and each passage increased the broadband SPL (10–250 Hz) by a minimum of 20 dB (Figure 4a,b). An individual container vessel (183 m and 27,795 gross tonnes) had its CPA (08:12) at 1.83 km from the hydrophone. During this passage, the vessel increased the PSD across a wide frequency range (10–24,000 Hz) and the communication space of bigeyes decreased from 42.3 to 3.3 m (Figure 4d). The communication space at the CPA remained low for two subsequent recordings before returning to over 40 m. Bryde's whale communication space was affected for longer than bigeyes with a decrease for 2 hr prior and post the vessel passage at 08:00 (Figure 4e). Bryde's whale vocalizations have a lower frequency range compared to bigeye vocalizations; therefore, the less temporally and spatially localized dips in communication space were synchronous to a steady increase in PSD in the lower frequencies and a decrease in the distance of the vessel to the listening station. All six cargo and container vessel passages in the 24-hr period at Jellicoe Channel showed a similar effect on bigeye and Bryde's whale communication space, with the ATL consistent throughout the day and night (Figure 4).

At Horn Rock during a 24-hr period, three separate cargo vessels (between 129–180, and 6,309–20,969 gross tonnes) passed within 10 km of the listening station, with only one cargo vessel (129 m and 6,309 gross tonnes) causing a marked increase in the broadband SPL (10–250 Hz) at 08:20 (Figure 5c). There was also an increase in PSD between 500–3,000 Hz of 20–30 dB at dawn (06:00) and dusk (19:00), as a result of the urchin chorus (Figure 5b). Bigeye and Bryde's whale communication space was lowest during each CPA and transient peaks (Figure 5d,e). However, it should be noted that Bryde's whale communication space fluctuated all day and night, following the small changes in the PSD between 10 and 200 Hz (Figures 5b and 5e). In contrast, bigeye communication space remained fairly consistent throughout the day at approximately 20 m, except for an increase to over 40 m prior and post urchin chorus (Figures 5b and 5d).

3.4 | Estimated Source Levels of CPAs

Using one unique vessel, effect of ship design and operational conditions could be controlled. The SL was estimated for an individual container vessel (length 183 m and 27,795 tonnes) for five passages with different speeds past Jellicoe Channel and once past Horn Rock (Figure 6). Estimated SL varied by up to 30 dB depending on the speed of passage and 1/3 octave centre frequency. There was not a clear relationship between speed and SL. However, when the container vessel was travelling <10 knots, the SL was lower across all frequencies than when the vessel was travelling >10 kts (Figure 6). The only exception was at 125 Hz for 9.8 kts. Using the concurrent recorded RL, the communication space of bigeyes and Bryde's whales was larger when the vessel was travelling less than 10 knots (Figure 7) at 40 and 250 Hz (the peak frequencies of each animal). The results also showed that influence of ship speed on SL varied depending on frequency. The difference in SL was more notable at lower frequencies: at 40 Hz SL increased 25.5 dB travelling between 6.6 and 13.9 kts, whereas at 1,000 Hz the SL increased 6.4 dB, respectively (Figure 6).

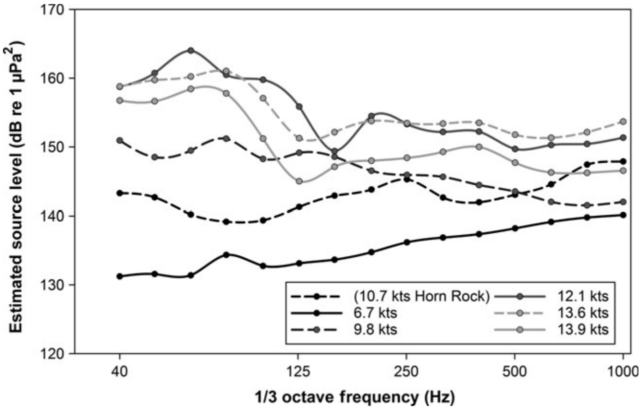

FIGURE 6 Estimated source level (dB re 1 μPa^2 @1 m) of an individual vessel (length 183 m and 27,795 tonnes) recorded travelling at five different speeds past the Jellicoe Channel listening station and one speed past Horn Rock

4 | DISCUSSION

The introduction of anthropogenic noise into the marine environment alters soundscapes from their natural state. A global effort is underway to understand the effects of underwater noise on aquatic life, in part because vessel noise is already becoming a dominant feature of many marine acoustic habitats. In the present study, vessel passages accounted for 3.9–18.9% of recordings during the 9-month monitoring period and increased the SPL (10–1,000 Hz) by 10.4–13.9 dB compared to the background. The Jellicoe Channel site is beside the most traversed shipping lane into the Ports of Auckland, and had the highest percentage of vessel passages (18.9%). Jellicoe Channel also had the lowest background SPL, resulting in the largest baseline communication space (43.5 m for bigeyes, 8.2 km for Bryde's whales) of the four listening stations (Figures S1 and S2). Consequently, this site has the greatest reduction (in metres) in communication space (Figures 4 and 5) during CPA vessel transits. Sites which have low ambient noise levels, such as Jellicoe Channel, can serve as useful indicators of environmental change (Merchant et al., 2016). Vessel passages were less prevalent at Horn Rock (3.9%), possibly because the listening station was over 10 km from the main shipping routes for the Ports of Auckland (Constantine et al., 2015). At Horn Rock, the baseline communication space for bigeyes was the lowest (21.4 m) because the ambient soundscape contained other biological sounds such as the urchin chorus, crustacean feeding sounds and fish vocalizations. However, the reduction in communication space caused by background, transient and CPA recordings showed a similar pattern across the four listening stations, when the percentage change was assessed. Bigeye communication space was reduced by 42.0, 61.5 and 99.9% at Jellicoe Channel for background,

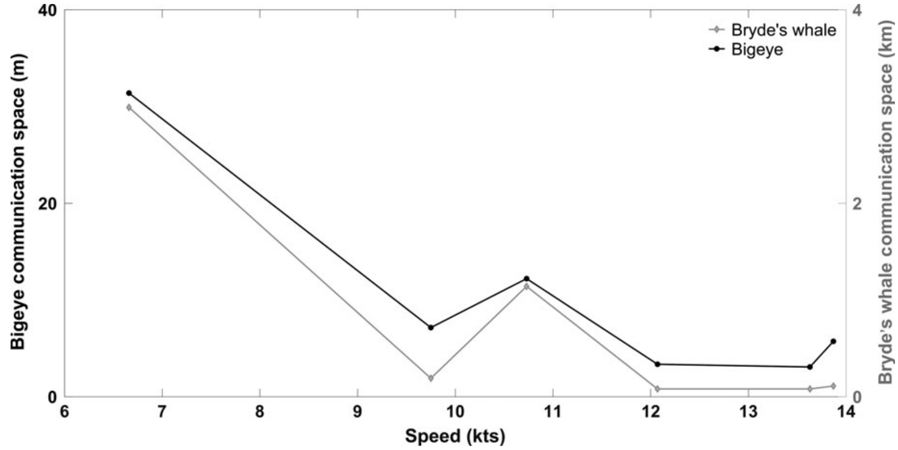

FIGURE 7 Communication space of an individual bigeye (m) and Bryde's whale (km) versus six speed of an individual container vessel, calculated using the received level of the six CPAs

transient and CPA recordings. Similarly, at Horn Rock communication space was reduced by 27.6, 31.3 and 99.8%.

Auditory masking occurs when biologically irrelevant sounds prevent an animal from hearing biologically relevant sounds (Popper, 2003). The literature of the effect of auditory masking on aquatic animals is limited, with the majority of research focused on marine mammals (Erbe, 2012). Experiments conducted on bigeyes provided the first evidence of a fish using sound as a contact call to maintain social cohesion (van Oosterom et al., 2016). However, the consequences of masking contact calls for schooling fish are as yet unknown. Bigeye contact calls can be heard throughout day and night on rocky reefs, with peak vocalization rates during crepuscular activity when they exit and return to their daytime refuges (van Oosterom et al., 2016; Radford et al., 2015). Bigeye communication space was greatest during dawn and dusk, with the communication space exceeding 60 m (Figure 5), suggesting the species has adapted to fit this acoustic niche. Therefore, vessel noise would have the greatest impact on acoustic communication of this species during these times as it was shown to reduce the communication space routinely by up to 61.5% during transient vessel passages and up to 99.9% at the CPA (Figure 2, Table S2). This is ecologically significant because fish shoaling behaviour is generally maintained to increase foraging success and lower predation risk (Pitcher, 1983). The consequences of vessel noise masking contact calls could affect individual fitness by lowering food intake and/or survival rates. Fish are a valuable and increasingly utilized model taxa for understanding behaviour in relation to anthropogenic noise because they represent more than half of all vertebrate species and exhibit a broad range of hearing and sound production mechanisms. Some studies suggest that there is plasticity in the sound production behaviour of fish. For example, the tidal cycle and other calling males caused a shift in the duration and calling rate of the toadfish (*Halobatrachus didactylus*) (Amorim, Simões, Almada, & Fonseca, 2011), whilst damselfish (*Dascyllus flavicaudus*) were capable of modifying the rhythm and number of pulses of their calls when faced with novel sounds in their environment (Parmentier, Kéver, Casadevall, & Lecchini, 2010). Bigeyes also exhibited behavioural plasticity, during tank play-back experiments increased ambient sound level caused their shoaling area to decrease and vocalization rate to increase (van Oosterom et al., 2016). When exposed to vessel passage sound, bigeyes may elicit a similar response to previous laboratory experiments. Future research should examine the extent to which specific species can compete with anthropogenic noise through adaptation or adjustment of their acoustic signals (Stanley et al., 2017).

The communication space for fish is modest in comparison to marine mammals, with whales capable of communicating over many kilometres (Richardson et al., 1995). In this study, the communication space of Bryde's whales was reduced by as much as 87.4% during transit vessel passages and up to 99.9% at the CPA (Figure 3, Table S3). Furthermore, the loss in communication space at Flat Rock (68.8%) and Shearer Rock (67.3%) (Table S3) caused by transient vessel passages was comparable to the loss in communication space (63–67%) calculated for North Atlantic right whales when exposed to vessel noise (Hatch et al., 2012). Both North Atlantic right whales (Parks, Urazghildiiev, & Clark, 2009) and Bryde's whales vocalize infrequently (Constantine et al., 2015) therefore, masking from vessel noise could result in missed breeding opportunities or affect social cohesion. Our results showed vessel noise in the Hauraki Gulf reduced their communication space to only a few hundred metres (from a baseline of over 8 km) when a vessel was present. Other baleen whale species have been found to respond to vessel noise, with changes in physiology, foraging and vocal behaviour. North Atlantic right whales (*Eubalaena glacialis*) were found to call louder (Parks, Johnson, Nowacek, & Tyack, 2011) and have heightened levels of physiological stress (Rolland et al., 2012) in response to vessel noise. Furthermore, vessel noise influenced humpback whale foraging behaviour (Blair, Merchant, Friedlaender, Wiley, & Parks, 2016) and caused both acoustic and behavioural changes in fin whales (Castellote, Clark, & Lammers, 2012). Importantly, behavioural disturbance and physiological stress caused by anthropogenic noise depend on the context (time and place), with different effects observed for different species. In this study, the effect of anthropogenic noise on the effective communication space of individual marine fauna has been quantified although it is difficult to directly relate this to the population or ecosystem level.

Naturally occurring changes in the underwater soundscape have been studied extensively around the world, with many studies reporting a maximum peak in SPL during summer and minimum during winter (Harris, Shears, & Radford, 2016; Lillis, Eggleston, & Bohnenstiehl, 2014; Nedelec et al., 2015; Radford, Stanley, Tindle, Montgomery, & Jeffs, 2010; Staaterman, Paris, DeFerrari, et al., 2014; Staaterman, Paris, & Kough, 2014). Therefore, studies addressing the masking effects of anthropogenic noise on soniferous species need to consider the context of this naturally fluctuating soundscape. In this study, variation in the background SPL reduced the communication space of both bigeye and Bryde's whales (Figures 2 and 3). The sound of earthquakes, wind and waves (Wenz, 1962) overlaps the peak frequency of Bryde's whale vocalizations (35 ± 0.3 Hz) (Putland et al., 2017) and as a result there were temporal fluctuations in an individual's communication space (Figure 5). Additionally, for bigeyes, at 1,000 Hz the background sound decreased communication space to the same degree or sometimes more than at the CPA (Figure 2). For example, at Horn Rock, background recordings reduced bigeye communication space by 12.5 m, whereas CPAs reduced it by 8.9 m (Figure 2b). Natural fluctuations in bigeye communication space may occur because other soniferous animals found on rocky reefs, such as fish (Radford, Ghazali, Montgomery, & Jeffs, 2016), crustaceans (Buscaino et al., 2012) or urchins (Radford, Jeffs, Tindle, & Montgomery, 2008b) produce sounds between 100 and 1,000 Hz. These biological sounds also exhibit temporal changes. For example, the crepuscular activity of urchins and fish caused an increase (20–30 dB re 1 μPa) in the ambient sound level (Cato, 1978; Radford, Jeffs, Tindle, & Montgomery, 2008b) on reefs in New Zealand and Australia, and the highest sound levels (130 dB re 1 μPa) on reefs in the Florida Keys, USA, occurred during the new moon (Staaterman, Paris, DeFerrari, et al., 2014; Staaterman, Paris, & Kough, 2014).

Importantly, vessel passages and CPAs both decreased communication space beyond the natural variability of the background recordings between 10 and 500 Hz. These results suggest vessel noise reduces communication space beyond the evolutionary context of these two species. Bigeyes produce vocalizations to maintain school cohesion and it is predicted that many other reef fish species do the same (McCauley & Cato, 2000; van Oosterom et al., 2016; Staaterman, Paris, DeFerrari, et al., 2014; Staaterman, Paris, & Kough, 2014). The vocal range of bigeyes is also very similar to many other soniferous fish; therefore, the reduction in communication space modelled is representative. Very little is known about why baleen whales vocalize or their hearing capabilities. In this study, Bryde's whales were used as a model organism because their downsweep vocalizations are within a frequency range (<200 Hz) and produced at rate that is representative of other baleen whales (Baumgartner & Mussoline, 2011; Stafford et al., 2007) such as fin (*Balaenoptera physalus*) (Moore et al., 1998) and blue (*Balaenoptera musculus*) whales (Širović et al., 2009; Stafford, Fox, & Clark, 1998). Taking into consideration the assumptions of the model (such as omnidirectional hearing of the receiver and no amplitude modulation of their vocalization to compensate for noise), the reduction in communication space during a vessel passage can be used as a proxy for other baleen whales.

It is currently assumed that reef fauna have evolved to cope with seasonal changes in the natural acoustic habitat caused by other biological or geological sounds. However, significant levels of anthropogenic noise have only been present in the world's oceans since the industrial revolution, and as such soniferous species will have to adapt to changes in the soundscape over a relatively short evolutionary timescale. Some marine species exhibit coping mechanisms, collectively known as the Lombard effect, to adapt to changing natural acoustic habitats. For example, some species have been found to change the frequency range (Parks et al., 2011) or increase the volume (Holt & Johnston, 2014; Parks et al., 2011) of their vocalizations. Whether the energetic costs associated with these adaptations are having effects on population growth rates of affected animals is an open question. Vessel noise masked the entire frequency range of bigeye vocalizations although the decrease in communication space was brief (20 min; Figures 4 and 5). Acute exposure to anthropogenic noise could cause immediate effects, such as not avoiding a predator because a conspecific warning vocalization was missed, and more incremental and cryptic effects, such as increased stress levels (Gedamke et al., 2016; Rolland et al., 2012). Chronic exposure to anthropogenic noise has also been found to cause significant acoustic and behavioural changes to aquatic species. For example, killer whales (*Orcinus orca*) increased the durations of calls in the presence of boats, indicating that these whales adjusted their behaviour to compensate for the introduced anthropogenic noise (Foote, Osborne, & Hoelzel, 2004).

The source level for vessel passages calculated in this study ranged from 135 to 145 dB re 1 μPa^2 @ 1 m between 40 and 1,000 Hz, above the suggested threshold (120 dB re 1 μPa^2) at which baleen whales have been observed to exhibit behavioural responses (Southall et al., 2007). The estimated SLs also covered the peak SL for large ships (Arveson & Vendittis, 2000), but were lower than previous estimates for tankers and container vessels, which could be a reflection of the propagation model used (Weston, 1971). The large interquartile range can be explained by the large variation in size (67–364 m) and gross tonnage (2,747–71,673) of vessels, which both are known to affect SL (McKenna et al., 2013; Simard, Roy, Gervaise, & Giard, 2016). There is also a relationship between ship speed and SL (20–1,000 Hz; McKenna et al., 2013). Focusing on multiple passages of the same individual vessel, design variability was controlled and the relationship between SL and speed illustrated. Currently, there is a 10 kt speed restriction within the Hauraki Gulf Marine Park to help prevent ship strike to resident Bryde's whales (Constantine et al., 2015). The level of compliance was investigated from 2014 to 2016 and average speed was ~10 kts (Ebdon, 2017). Importantly, the calculated SLs of an individual container vessel (Figure 6) demonstrated how compliance to the 10 kt speed restriction may have the added benefit of reducing sound levels in the embayment, particularly at low frequencies where the discrepancy in SL (and the risk to Bryde's whale communication) was the highest. In this study, the communication space of both species was higher when the speed of one individual container vessel was below the 10 knot restriction (Figure 7). This information provides vital evidence for future strategies to reduce vessel noise in the area although for smaller vessels there is a trade-off between vessels travelling slower (decrease in the SL) and spending more time in the area (increasing exposure duration; McKenna et al., 2013) and for larger vessels there is a limitation for reducing speed to maintain manoeuvrability. In the longer term, ship quieting technologies to reduce ship noise emissions have the greatest potential to reduce levels of shipping noise pollution.

A major concern for environmental management of the world's coastal waters is the anticipated rise in anthropogenic activity, with an expectation commercial vessel activity will rise by 75% in the next 20 years for the Hauraki Gulf (Ports of Auckland, 2010). Increased shipping into coastal ports means decreasing the time between vessel passages and thereby increasing noise exposure time for resident marine life. Sound, unlike more persistent forms of marine pollution, ceases to exist once the source is removed, and so management measures to reduce vessel noise have the potential to produce rapid improvements in habitat quality. Improvements to vessel design, such as dampening engine vibrations, changing hull design and reducing the number of engine cylinders, have been found to reduce noise produced (Okumoto, Takeda, Mano, & Okada, 2009), and as such improvements and engineering developments should continue to be encouraged by government organizations. Modelling anthropogenic noise using AIS data is one way to identify at-risk areas for particular species (Erbe et al., 2014), and could be used to test scenarios of vessel noise reduction measures. However, the accuracy of acoustic maps based on AIS data is limited because only vessels over 300 gross tonnes and carrying more than 165 passengers are required to carry AIS transmitters. The Hauraki Gulf currently has 132,000 recreational vessels, most of which are not required to operate AIS transmitters. With the number of recreational vessels expected to rise by 40% in the next 20 years (BECA International Limited, 2012) and their regular contact with marine life via fishing and tourism, it is critical that the risk posed by this activity is better understood to enable effective management of sound pollution.

The present study has shown that vessel passages have the potential to reduce both fish and whale communication space beyond the natural variability in background sound. Bigeye communication space was only impacted for a short time period, but with vessel passages anticipated to rise in ecological significant embayments, the temporal effect may also increase. Bryde's whales were more severely affected, with communication space reduced for several hours around a vessel passage. Bryde's whales are an endangered species in New Zealand waters; therefore, information from this study could directly inform local mitigation strategies. At Jellicoe Channel, Bryde's whale vocalizations were regularly recorded. This station lies on the border of the voluntary speed restriction which limits vessels to 10 kts. To combat the effect of vessel noise on communication space, we suggest this boundary could be extended or an alternative compulsory speed limit enforced. Reducing vessel noise would ultimately allow the communication space of soniferous species like the bigeye and Bryde's whale to be maintained, as well as improve the quality of the acoustic habitat for other acoustically sensitive species.

ACKNOWLEDGEMENTS

Many thanks to Kordia Limited (curators for Maritime NZ) for providing the AIS data. Bathymetry data were kindly provided by Land Information New Zealand on 11th November 2016 and licensed for re-use under the Creative Commons Attribution 4.0 International Licence. CAR is a Rutherford Discovery Fellow funded by the Royal Society of New Zealand (RDF-UOA1302).

ORCID

Rosalyn L. Putland http://orcid.org/0000-0001-6043-6939
Nathan D. Merchant http://orcid.org/0000-0002-1090-0016
Adrian Farcas http://orcid.org/0000-0002-3320-8428
Craig A. Radford http://orcid.org/0000-0001-7949-9497

REFERENCES

American National Standard ANSI. (2004). Specification for octave-band and fractional-octave-band analog and digital filters. Retrieved from https://global.ihs.com/doc_detail.cfm?&csf=ASA&document_name=ANSI%2FASA%20S1%2E11&item_s_key=00009495#abstract-section

Amorim, M. C. P., Simões, J. M., Almada, V. C., & Fonseca, P. J. (2011). Stereotypy and variation of the mating call in the Lusitanian toadfish, *Halobatrachus didactylus*. *Behavioral Ecology and Sociobiology*, *65*(4), 707–716. https://doi.org/10.1007/s00265-010-1072-3

Amorim, M. C. P., Vasconcelos, R. O., Marques, J. F., & Almada, F. (2006). Seasonal variation of sound production in the Lusitanian toadfish *Halobatrachus didactylus*. *Journal of Fish Biology*, *69*(6), 1892–1899. https://doi.org/10.1111/j.1095-8649.2006.01247.x

Andrew, R. K., Howe, B. M., Mercer, J. A., & Dzieciuch, M. A. (2002). Ocean ambient sound: Comparing the 1960s with the 1990s for a receiver off the California coast. *Acoustics Research Letters Online*, *3* (2), 65–70. https://doi.org/10.1121/1.1461915

Arveson, P. T., & Vendittis, D. J. (2000). Radiated noise characteristics of a modern cargo ship. *The Journal of the Acoustical Society of America*, *107*(1), 118–129. https://doi.org/10.1121/1.428344

Auckland Council (2017). *Auckland unitary plan*. Retrieved 22 July, 2017, from http://www.aucklandcouncil.govt.nz/EN/planspoliciesprojects/plansstrategies/unitaryplan/Pages/home.aspx

Barber, J. R., Crooks, K. R., & Fristrup, K. M. (2010). The costs of chronic noise exposure for terrestrial organisms. *Trends in Ecology & Evolution*, *25*(3), 180–189. https://doi.org/10.1016/j.tree.2009.08.002

Baumgartner, M. F., & Mussoline, S. E. (2011). A generalized baleen whale call detection and classification system. *The Journal of the Acoustical Society of America*, *129*(5), 2889–2902. https://doi.org/10.1121/1.3562166

BECA International Limited (2012). *Auckland recreational boating study: Report for Auckland Council*. Auckland: BECA International Limited.

Blair, H. B., Merchant, N. D., Friedlaender, A. S., Wiley, D. N., & Parks, S. E. (2016). Evidence for ship noise impacts on humpback whale foraging behaviour. *Biology Letters*, *12*(8). https://doi.org/10.1098/rsbl.2016.0005

Buscaino, G., Filiciotto, F., Buffa, G., Di Stefano, V., Maccarrone, V., Buscaino, C., ... Maccarrone, V. (2012). The underwater acoustic activities of the red swamp crayfish *Procambarus clarkii*. *The Journal of the Acoustical Society of America*, *132*(3), 1792–1798. https://doi.org/10.1121/1.4742744

Caiger, P. E., Montgomery, J. C., & Radford, C. A. (2012). Chronic low-intensity noise exposure affects the hearing thresholds of juvenile snapper. *Marine Ecology Progress Series*, *466*, 225–232. https://doi.org/10.3354/meps09933

Castellote, M., Clark, C. W., & Lammers, M. O. (2012). Acoustic and behavioural changes by fin whales (*Balaenoptera physalus*) in response to shipping and airgun noise. *Biological Conservation*, *147*(1), 115–122. https://doi.org/10.1016/j.biocon.2011.12.021

Cato, D. H. (1978). Marine biological choruses observed in tropical waters near Australia. *The Journal of the Acoustical Society of America*, *64*(3), 736–744. https://doi.org/10.1121/1.382038

Clark, C. W., Ellison, W. T., Southall, B. L., Hatch, L., Van Parijs, S. M., Frankel, A., & Ponirakis, D. (2009). Acoustic masking in marine ecosystems: Intuitions, analysis, and implication. *Marine Ecology Progress Series*, *395*, 201–222. https://doi.org/10.3354/meps08402

Constantine, R., Johnson, M., Riekkola, L., Jervis, S., Kozmian-Ledward, L., Dennis, T., ... Aguilar de Soto, N. (2015). Mitigation of vessel-strike mortality of endangered Bryde's whales in the Hauraki Gulf, New Zealand. *Biological Conservation*, *186*, 149–157. https://doi.org/10.1016/j.biocon.2015.03.008

Cummings, W. C., Thompson, P. O., & Ha, S. J. (1986). Sounds from Bryde's, *Balaenoptera edeni*, and finback, *Balaenoptera physalus*, whales in the Gulf of California. *Fishery Bulletin*, *84*, 359–370.

Dooling, R. J., Westm, E. W., & Leek, M. R. (2009). *Conceptual and computation models of the effects of anthropogenic sound on birds*. Paper presented at the 5th International Conference on Bioacoustics 2009, Proceedings of Institute of Acoustics.

Ebdon, P. (2017). *Testing the efficacy of ship strike mitigation for whales in the Hauraki Gulf, New Zealand*. Masters of Science, University of Auckland.

Engås, A., Løkkeborg, S., Ona, E., & Soldal, A. V. (1996). Effects of seismic shooting on local abundance and catch rates of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*). *Canadian Journal of Fisheries and Aquatic Sciences*, *53*(10), 2238–2249. https://doi.org/10.1139/f96-177

Erbe, C. (2012). Effects of underwater noise on marine mammals. In A. N. Popper & A. Hawkins (Eds.), *The effects of noise on aquatic life* (pp. 17–22). New York, NY: Springer New York. https://doi.org/10.1007/978-1-4419-7311-5

Erbe, C., Williams, R., Sandilands, D., & Ashe, E. (2014). Identifying modeled ship noise hotspots for marine mammals of Canada's Pacific region. *PLoS One*, *9*(3), e89820. https://doi.org/10.1371/journal.pone.0089820

Farcas, A., Thompson, P. M., & Merchant, N. D. (2016). Underwater noise modelling for environmental impact assessment. *Environmental Impact Assessment Review*, *57*, 114–122. https://doi.org/10.1016/j.eiar.2015.11.012

Foote, A. D., Osborne, R. W., & Hoelzel, A. R. (2004). Environment: Whale-call response to masking boat noise. *Nature*, *428*(6986), 910. https://doi.org/10.1038/428910a

Francis, C. D., & Barber, J. R. (2013). A framework for understanding noise impacts on wildlife: An urgent conservation priority. *Frontiers in Ecology and the Environment*, *11*(6), 305–313. https://doi.org/10.1890/120183

Francis, C. D., Ortega, C. P., & Cruz, A. (2009). Noise pollution changes avian communities and species interactions. *Current Biology*, *19*(16), 1415–1419. https://doi.org/10.1016/j.cub.2009.06.052

Frisk, G. V. (2012). Noiseonomics: The relationship between ambient noise levels in the sea and global economic trends. *Scientific Reports*, *2*, 437. https://doi.org/10.1038/srep00437

Gedamke, J., Harrison, J., Hatch, L., Angliss, R., Barlow, J., Berchok, C., ... Wahle, C. M. (2016). *Ocean noise strategy roadmap*. Boston, MA: NOAA. Retrieved from http://cetsound.noaa.gov/

Harris, S. A., Shears, N. T., & Radford, C. A. (2016). Ecoacoustic indices as proxies for biodiversity on temperate reefs. *Methods in Ecology and Evolution*, *7*(6), 713–724. https://doi.org/10.1111/2041-210x.12527

Hatch, L. T., Clark, C., Merrick, R., Van Parijs, S., Ponirakis, D., Schwehr, K., ... Wiley, D. (2008). Characterizing the relative contributions of large vessels to total ocean noise fields: A case study using the Gerry E. Studds Stellwagen Bank national marine sanctuary. *Environmental Management*, *42*(5), 735–752. https://doi.org/10.1007/s00267-008-9169-4

Hatch, L. T., Clark, C. W., Van Parijs, S. M., Frankel, A. S., & Ponirakis, D. W. (2012). Quantifying loss of acoustic communication space for right whales in and around a U.S. National Marine Sanctuary. *Conservation Biology*, *26*(6), 983–994. https://doi.org/10.1111/j.1523-1739.2012.01908.x

Hildebrand, J. A. (2009). Anthropogenic and natural sources of ambient noise in the ocean. *Marine Ecology Progress Series*, *395*, 5–20. https://doi.org/10.3354/meps08353

Holt, D. E., & Johnston, C. E. (2014). Evidence of the Lombard effect in fishes. *Behavioral Ecology*, *25*(4), 819–826. https://doi.org/10.1093/beheco/aru028

Janik, M. V. (2000). Source levels and the estimated active space of bottlenose dolphin (*Tursiops truncatus*) whistles in the Moray Firth. *Scotland. Journal of Comparative Physiology A*, *186*(7), 673–680. https://doi.org/10.1007/s003590000120

Kaplan, M. B., & Solomon, S. (2016). A coming boom in commercial shipping? The potential for rapid growth of noise from commercial ships by 2030. *Marine Policy*, *73*, 119–121. https://doi.org/10.1016/j.marpol.2016.07.024

Kastak, D., Southall, B. L., Schusterman, R. J., & Kastak, C. R. (2005). Underwater temporary threshold shift in pinnipeds: Effects of noise level and duration. *The Journal of the Acoustical Society of America*, *118*(5), 3154–3163. https://doi.org/10.1121/1.2047128

Kastelein, R. A., de Haan, D., & Verboom, W. C. (2007). The influence of signal parameters on the sound source localization ability of a harbor porpoise (*Phocoena phocoena*). *The Journal of the Acoustical Society of America*, *122*(2), 1238–1248. https://doi.org/10.1121/1.2747202

Kelly, S., Sim-Smith, C., Faire, S., Pierre, J., & Hikuroa, D. (2014). *State of our gulf 2014 Hauraki Gulf-Tikapa Moana/Te Moananui a Toi state of the environment report 2014 (192721663X)*. Auckland, New Zealand: Hauraki Gulf Forum. Retrieved from http://www.aucklandcouncil.govt.nz/EN/environmentwaste/coastalmarine

Lillis, A., Eggleston, D. B., & Bohnenstiehl, D. R. (2014). Estuarine soundscapes: Distinct acoustic characteristics of oyster reefs compared to soft-bottom habitats. *Marine Ecology Progress Series*, *505*, 1–17. https://doi.org/10.3354/meps10805

Lucke, K., Siebert, U., Lepper, P. A., & Blanchet, M.-A. (2009). Temporary shift in masked hearing thresholds in a harbor porpoise (*Phocoena phocoena*) after exposure to seismic airgun stimuli. *The Journal of the Acoustical Society of America*, *125*(6), 4060–4070. https://doi.org/10.1121/1.3117443

Mann, D. A. (2006). Propagation of fish sounds. In F. Ladich, S. P. Collin, P. Moller & B. G. Kapoor (Eds.), *Communication in fishes*, Vol. 1 (pp. 107–120). Enfield, NH: Science Publishers.

McCauley, R. D., & Cato, D. H. (2000). Patterns of fish calling in a nearshore environment in the Great Barrier Reef. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, *355* (1401), 1289. https://doi.org/10.1098/rstb.2000.0686

McCauley, R. D., Fewtrell, J., & Popper, A. N. (2003). High intensity anthropogenic sound damages fish ears. *The Journal of the Acoustical Society of America*, *113*(1), 638–642. https://doi.org/10.1121/1.1527962

McKenna, M. F., Ross, D., Wiggins, S. M., & Hildebrand, J. A. (2012). Underwater radiated noise from modern commercial ships. *The Journal of the Acoustical Society of America*, *131*(1), 92–103. https://doi.org/10.1121/1.3664100

McKenna, M. F., Wiggins, S. M., & Hildebrand, J. A. (2013). Relationship between container ship underwater noise levels and ship design, operational and oceanographic conditions. *Scientific Reports*, *3*, 1760. https://doi.org/10.1038/srep01760

Merchant, N. D., Brookes, K. L., Faulkner, R. C., Bicknell, A. W. J., Godley, B. J., & Witt, M. J. (2016). Underwater noise levels in UK waters. *Scientific Reports*, *6*, 36942. https://doi.org/10.1038/srep36942

Merchant, N. D., Witt, M. J., Blondel, P., Godley, B. J., & Smith, G. H. (2012). Assessing sound exposure from shipping in coastal waters using a single hydrophone and automatic identification system (AIS) data. *Marine Pollution Bulletin*, *64*(7), 1320–1329. https://doi.org/10.1016/j.marpolbul.2012.05.004

Moore, S. E., & Clarke, J. T. (2002). Potential impact of offshore human activities on gray whales (*Eschrichtius robustus*). *Journal of Cetacean Research and Management*, *4*(1), 19–25.

Moore, S., Stafford, K., Dahlheim, M., & Fox, C. (1998). Seasonal variation in reception of fin whale calls at five geographic areas in the north Pacific. *Marine Mammal Science*, *14*, 617–627. https://doi.org/10.1111/j.1748-7692.1998.tb00749.x

Nachtigall, P. E., Supin, A. Y., Pawloski, J., & Au, W. W. L. (2004). Temporary threshold shifts after noise exposure in the bottlenose dolphin (*Tursiops truncatus*) measured using evoked auditory potentials. *Marine Mammal Science*, *20*(4), 673–687. https://doi.org/10.1111/j.1748-7692.2004.tb01187.x

Naguib, M. (2013). Living in a noisy world: Indirect effects of noise on animal communication. *Behaviour*, *150*, 1069–1084.

Nedelec, S. L., Simpson, S. D., Holderied, M., Radford, A. N., Lecellier, G., Radford, C., & Lecchini, D. (2015). Soundscapes and living communities in coral reefs: Temporal and spatial variation. *Marine Ecology Progress Series*, *524*, 125–135. https://doi.org/10.3354/meps11175

Okumoto, Y., Takeda, Y., Mano, M., & Okada, T. (2009). *Design of ship hull structures: A practical guide for engineers*, 1st ed. Berlin, Germany: Springer-Verlag. https://doi.org/10.1007/978-3-540-88445-3

van Oosterom, L., Montgomery, J. C., Jeffs, A. G., & Radford, C. A. (2016). Evidence for contact calls in fish: Conspecific vocalisations and ambient soundscape influence group cohesion in a nocturnal species. *Scientific Reports*, *6*, 19098. https://doi.org/10.1038/srep19098

Parks, S. E., Johnson, M., Nowacek, D., & Tyack, P. L. (2011). Individual right whales call louder in increased environmental noise. *Biology Letters*, *7*(1), 33. https://doi.org/10.1098/rsbl.2010.0451

Parks, S. E., Urazghildiiev, I., & Clark, C. W. (2009). Variability in ambient noise levels and call parameters of north Atlantic right whales in three habitat areas. *The Journal of the Acoustical Society of America*, *125*, 1230–1239. https://doi.org/10.1121/1.3050282

Parmentier, E., Kéver, L., Casadevall, M., & Lecchini, D. (2010). Diversity and complexity in the acoustic behaviour of *Dacyllus flavicaudus* (Pomacentridae). *Marine Biology*, *157*(10), 2317–2327. https://doi.org/10.1007/s00227-010-1498-1

Payne, R. S., & McVay, S. (1971). Songs of humpback whales. *Science*, *173*(3997), 585–597. https://doi.org/10.1126/science.173.3997.585

Payne, R., & Webb, D. (1971). Orientation by means of long range acoustic signaling in baleen whales. *Annals of the New York Academy of Sciences*, *188*(1), 110–141. https://doi.org/10.1111/j.1749-6632.1971.tb13093.x

Pitcher, T. J. (1983). Functions of shoaling behaviour in teleosts. In T. J. Pitcher (Ed.), *Behaviour of teleost fishes* (pp. 294–337). Boston, MA: Springer US. https://doi.org/10.1007/978-1-4684-8261-4_12

Popper, A. N. (2003). Effects of anthropogenic sounds on fishes. *Fisheries*, *28*(10), 24–31. https://doi.org/10.1577/1548-8446(2003) 28[24:EOASOF]2.0.CO;2

Ports of Auckland (2010). *The role of ports and shipping in stimulating economic prosperity*. Auckland, New Zealand: Ports of Auckland Ltd.

Proppe, D. S., Sturdy, C. B., & St. Clair, C. C. (2013). Anthropogenic noise decreases urban songbird diversity and may contribute to homogenization. *Global Change Biology*, *19*(4), 1075–1084. https://doi.org/10.1111/gcb.12098

Purser, J., & Radford, A. N. (2011). Acoustic noise induces attention shifts and reduces foraging performance in three-spined sticklebacks (*Gasterosteus aculeatus*). *PLoS One*, *6*(2), e17478. https://doi.org/10.1371/journal.pone.0017478

Putland, R. L., Constantine, R., & Radford, C. A. (2017). Exploring spatial and temporal trends in the soundscape of an ecologically significant embayment. *Scientific Reports*, *7*(1), 5713. https://doi.org/10.1038/s41598-017-06347-0

Radford, C. A., Ghazali, S., Jeffs, A. G., & Montgomery, J. C. (2015). Vocalisations of the bigeye, *Pempheris adspersa*: Characteristics, source level, and active space. *Journal of Experimental Biology*, *218*(6), 940–948. https://doi.org/10.1242/jeb.115295

Radford, C. A., Ghazali, S. M., Montgomery, J. C., & Jeffs, A. G. (2016). Vocalisation repertoire of female bluefin gurnard (*Chelidonichthys kumu*) in captivity: Sound structure, context and vocal activity. *PLoS One*, *11*(2), e0149338. https://doi.org/10.1371/journal.pone.0149338

Radford, C. A., Jeffs, A. G., Tindle, C. T., & Montgomery, J. C. (2008a). Ambient noise in shallow temperate waters around northeastern New Zealand. *Bioacoustics*, *17*(1–3), 26–28. https://doi.org/10.1080/09524622.2008.9753752

Radford, C. A., Jeffs, A. G., Tindle, C. T., & Montgomery, J. C. (2008b). Resonating sea urchin skeletons create coastal choruses. *Marine Ecology Progress Series*, *362*, 37–43. https://doi.org/10.3354/meps07444

Radford, A. N., Kerridge, E., & Simpson, S. D. (2014). Acoustic communication in a noisy world: Can fish compete with anthropogenic noise? *Behavioral Ecology*, *25*(5), 1022–1030. https://doi.org/10.1093/beheco/aru029

Radford, C. A., Montgomery, J. C., Caiger, P., Johnston, P., Lu, J., & Higgs, D. M. (2013). A novel hearing specialisation in the New Zealand bigeye, *Pempheris adspersa*. *Biology Letters*, *9*, 20130163. https://doi.org/10.1098/rsbl.2013.0163

Radford, C. A., Stanley, J. A., Tindle, C. T., Montgomery, J. C., & Jeffs, A. G. (2010). Localised coastal habitats have distinct underwater sound signatures. *Marine Ecology Progress Series*, *401*, 21–29. https://doi.org/10.3354/meps08451

Richardson, W. J., Greene, C. R. Jr., Malme, C. J., & Thomson, D. H. (1995). *Marine mammals and noise*. San Diego, CA: Academic Press.

Rolland, R. M., Parks, S. E., Hunt, K. E., Castellote, M., Corkeron, P. J., Nowacek, D. P., … Kraus, S. D. (2012). Evidence that ship noise increases stress in right whales. *Proceedings of the Royal Society B: Biological Sciences*, *279*(1737), 2363. https://doi.org/10.1098/rspb.2011.2429

Rowe, S., Hutchings, J. A., Skjæraasen, J. E., & Bezanson, L. (2008). Morphological and behavioural correlates of reproductive success in Atlantic cod *Gadus morhua*. *Marine Ecology Progress Series*, *354*, 257–265. https://doi.org/10.3354/meps07175

Simard, Y., Roy, N., Gervaise, C., & Giard, S. (2016). Analysis and modeling of 255 source levels of merchant ships from an acoustic observatory along St. Lawrence Seaway. *The Journal of the Acoustical Society of America*, *140*(3), 2002–2018. https://doi.org/10.1121/1.4962557

Širović, A., Bassett, H. R., Johnson, S. C., Wiggins, S. M., & Hildebrand, J. A. (2014). Bryde's whale calls recorded in the Gulf of Mexico. *Marine Mammal Science*, *30*(1), 399–409. https://doi.org/10.1111/mms.12036

Širović, A., Hildebrand, J. A., Wiggins, S. M., & Thiele, D. (2009). Blue and fin whale acoustic presence around Antarctica during 2003 and 2004. *Marine Mammal Science*, *25*(1), 125–136. https://doi.org/10.1111/j.1748-7692.2008.00239.x

Skalski, J. R., Pearson, W. H., & Malme, C. I. (1992). Effects of sounds from a geophysical survey device on catch-per-unit-effort in a hook-and-line fishery for rockfish (*Sebastes* spp.). *Canadian Journal of Fisheries and Aquatic Sciences*, *49*(7), 1357–1365. https://doi.org/10.1139/f92-151

Smith, M. E., Kane, A. S., & Popper, A. N. (2004). Noise-induced stress response and hearing loss in goldfish (*Carassius auratus*). *Journal of Experimental Biology*, *207*(3), 427–435. https://doi.org/10.1242/jeb.00755

Southall, B. L., Bowles, A. E., Ellison, W. T., Finneran, J. J., Gentry, R. L., Greene, C. R. Jr, . . . Tyack, P. L. (2007). Marine mammal noise exposure criteria: Initial scientific recommendations. *Aquatic Mammals*, *33*(4), 411–521. https://doi.org/10.1578/am.33.4.2007.411

Southall, B. L., Schusterman, R. J., & Kastak, D. (2003). Acoustic communication ranges for northern elephant seals (*Mirounga angustirostris*). *Aquatic Mammals*, *29*(2), 202–213. https://doi.org/10.1578/016754203101024158

Staaterman, E., Paris, C. B., DeFerrari, H. A., Mann, D. A., Rice, A. N., & D'Alessandro, E. K. (2014). Celestial patterns in marine soundscapes. *Marine Ecology Progress Series*, *508*, 17–32. https://doi.org/10.3354/meps10911

Staaterman, E., Paris, C. B., & Kough, A. S. (2014). First evidence of fish larvae producing sounds. *Biology Letters*, *10*(10).

Stafford, K. M., Fox, C. G., & Clark, D. S. (1998). Long-range acoustic detection and localization of blue whale calls in the northeast Pacific Ocean. *The Journal of the Acoustical Society of America*, *104*(6), 3616–3625. https://doi.org/10.1121/1.423944

Stafford, K. M., Mellinger, D. K., Moore, S. E., & Fox, C. G. (2007). Seasonal variability and detection range modeling of baleen whale calls in the Gulf of Alaska, 1999–2002. *The Journal of the Acoustical Society of America*, *122*(6), 3378–3390. https://doi.org/10.1121/1.2799905

Stanley, J. A., Van Parijs, S. M., & Hatch, L. T. (2017). Underwater sound from vessel traffic reduces the effective communication range in Atlantic cod and haddock. *Scientific Reports*, *7*(1), 14633. https://doi.org/10.1038/s41598-017-14743-9

Tindle, C. T. (1982). Attenuation parameters from normal mode measurements. *The Journal of the Acoustical Society of America*, *71*(5), 1145–1148. https://doi.org/10.1121/1.387760

Tindle, C. T., Guthrie, K. M., Bold, M. D., Jones, J. D., Dixon, K. O., & Birdsall, T. G. (1978). Measurements of the frequency dependence of normal modes. *The Journal of the Acoustical Society of America*, *64*(4), 1178–1185. https://doi.org/10.1121/1.382080

Weilgart, L. S. (2007). The impacts of anthropogenic ocean noise on cetaceans and implications for management. *Canadian Journal of Zoology*, *85*(11), 1091–1116. https://doi.org/10.1139/z07-101

Wenz, G. M. (1962). Acoustic Ambient Noise in the Ocean: Spectra and Sources. *The Journal of the Acoustical Society of America*, *34*(12), 1936–1956. https://doi.org/10.1121/1.1909155

Weston, D. E. (1971). Intensity-range relations in oceanographic acoustics. *Journal of Sound and Vibration*, *18*(2), 271–287. https://doi.org/10.1016/0022-460x(71)90350-6

SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

How to cite this article: Putland RL, Merchant ND, Farcas A, Radford CA. Vessel noise cuts down communication space for vocalizing fish and marine mammals. *Glob Change Biol*. 2017;00:1–14. https://doi.org/10.1111/gcb.13996