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## Assessing auditory masking for management of underwater anthropogenic noise<sup>a)</sup>

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### ABSTRACT:

Masking is often assessed by quantifying changes, due to increasing noise, to an animal's communication or listening range. While the methods used to measure communication or listening ranges are functionally similar if used for vocalizations, they differ in their approaches: communication range is focused on the sender's call, while the listening range is centered on the listener's ability to perceive any signal. How these two methods differ in their use and output is important for management recommendations. Therefore it was investigated how these two methods may alter the conclusions of masking assessments based on Atlantic cod calls in the presence of a commercial air gun array. The two methods diverged with increasing distance from the masking noise source with maximum effects lasting longer between air gun pulses in terms of communication range than listening range. Reductions in the cod's communication ranges were sensitive to fluctuations in the call's source level. That instability was not observed for the listening range. Overall, changes to the cod's communication range were more conservative but very sensitive to the call source level. A high level of confidence in the call is therefore required, while confidence in the receiver's audiogram and soundscape is required for the listening range method. © 2020 Acoustical Society of America.

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### I. INTRODUCTION

Evidence that marine fauna are affected in lethal and sublethal ways by anthropogenic noise has resulted in substantial concern about rising noise levels underwater (Jones, 2019). Low frequency sounds travel underwater over long ranges, which can disturb the behavior of marine life far from a source (Slabbekoorn *et al.*, 2010). The most pervasive sublethal effect of underwater noise is auditory masking where an unwanted masking noise inhibits an animal from perceiving a biologically important sound (Erbe *et al.*, 2016). Masking can negatively impact reproductive behaviors and impair predator detections or foraging, use of sound cues for orientation and navigation, as well as intraspecific communication (Slabbekoorn *et al.*, 2010; Erbe *et al.*, 2016).

Noise can result in the masking of signals interpreted by animals, including birds (Barber *et al.*, 2009; Dooling and Popper, 2016; Dooling *et al.*, 2019), fish (Slabbekoorn *et al.*, 2010; Hawkins and Picciulin, 2019), marine mammals (Clark *et al.*, 2009; Erbe *et al.*, 2016), and humans when the masking noise contains sufficient energy inside the detectable frequency region of the signal and beyond the critical ratio—the critical ratio being the difference between the

sound pressure level (SPL) of a pure tone that is just audible in the presence of white noise (or some other continuous broadband noise; Erbe *et al.*, 2016) in dB. From research on birds, we know that noise outside the signal's frequency region contributes far less to masking (Dooling *et al.*, 2015; Erbe *et al.*, 2016), and this also applies to fish (Dooling *et al.*, 2015). In the marine environment, masking effects have been commonly assessed by quantifying the change in a caller's active communication space (i.e., the volume of ocean centered on a vocalizing animal within which conspecific communication is possible) during exposure to masking noise (Clark *et al.*, 2009). Ship noise has been found to decrease the communication space in both fish (Stanley *et al.*, 2017; Putland *et al.*, 2017) and marine mammals (Jensen *et al.*, 2009; Hatch *et al.*, 2012; Gabriele *et al.*, 2018). However, impulsive noise sources, such as percussive pile-driving or air guns used during seismic surveys, can also induce auditory masking effects. Characterized by a sharp rise time and high peak-to-peak amplitude, impulsive noise sources are increasingly common, and potential ecological effects have long been a cause for concern (Hastie *et al.*, 2019).

A common source of impulsive noise in the open ocean is air guns used during seismic surveys of subsurface geology. Air guns can be used in the same area for days or weeks, although intermittent and episodic (Carroll *et al.*, 2017), depending on the survey design (i.e., two or three dimensional; Gisiner, 2016). High-intensity noise such as

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those produced from air guns have been shown to produce physiological stress responses, increased detection thresholds, and, in some cases, tissue damage in marine mammals and fish (Pearson *et al.*, 1992; Casper *et al.*, 2012; Richardson *et al.*, 1995). These impacts may lead to displacement in marine mammals (Richardson *et al.*, 1995), changes to vocalizations in marine mammals and fish (Blackwell *et al.*, 2015; Radford *et al.*, 2014) or mortality, which in the case of fish displacement can have economic consequences (for example, Skalski *et al.*, 1992; Engås *et al.*, 1996).

Better understanding of underwater noise pollution has meant that masking effects are becoming more commonly assessed as part of the environmental impact assessment (EIA) process (Faulkner *et al.*, 2017; Clark *et al.*, 2017). Assessing changes in communication space (Clark *et al.*, 2009) is a method often used to assess the effects of masking. The sonar equation (see Clark *et al.*, 2009) is used to calculate communication space and requires information on the receiver's auditory filters (detection thresholds and signal gains), the sender's call structure at the source, and acoustic propagation loss in the environment (Erbe *et al.*, 2016). As is often the case for many species, particularly fish (whose species-specific vocalizations as a whole are poorly understood), call characteristics and auditory filter parameters are unknown or highly variable (Erbe *et al.*, 2016). Therefore, generalizations are often made for data-poor species (see cautions from Popper and Hastings, 2009).

Another method for assessing masking is to consider masking from the perspective of the listener instead of the sender, which allows for an analysis of the effects on species whose call source structures are unknown but their hearing capabilities are somewhat understood (Pine *et al.*, 2018). An animal's listening space is defined as the volume of ocean surrounding a listener within which a biologically important signal can be detected. It is the percentage difference in the distance in which a sound can be perceived under a given noise condition and a maximum listening range under quiet conditions, and is referred to as listening space reduction (LSR). Since the LSR method is not limited to a defined call structure, it is free from the constraints of communication space and its applicability can be as broad or as contextual as desired, which has distinct advantages for management. For example, this type of analysis also provides information on how an anthropogenic noise source affects an animal's ability to passively monitor their environment for sounds from predators or for navigation and habitat selection.

While the two methods produce functionally similar outputs (i.e., a proportional change to an animal's active space when exposed to masking noise), the quantitative results of both methods have never been directly compared. This comparison is important in order to understand how assumptions made in the methods affect the outcomes when applying these models as part of EIAs. A good animal model for such a comparison is the Atlantic cod (*Gadus morhua*), based on their low frequency hearing and capabilities in detection of both sound pressure and particle motion (Popper and Hawkins, 2018). In eastern Canada, stocks of

Atlantic cod have exhibited slow population growth [due to a combination of environmental and population-dependent factors (COSEWIC, 2010)] following a steep decline in the late 1980s and early 1990s due to overfishing. In Atlantic cod breeding habitats, an environmental factor that has changed in the past century is increased underwater anthropogenic noise (Zakarauskas *et al.*, 1990). Atlantic cod vocalize to advertise fitness and facilitate mating (Chapman and Hawkins, 1973; Rowe and Hutchings, 2006; Stanley *et al.*, 2017). Atlantic cod vocalizations have been studied in both the laboratory and field, and while their repertoire was initially considered small, a variety of sounds have been recorded from them (Hawkins and Picciulin, 2019). For example, grunts of varying durations and pulse-rates (Finstad and Nordeide, 2004; Fudge and Rose, 2009; Hernandez *et al.*, 2013), low frequency hums or rumbles (Nordeide and Kjellsby, 1999; Rowe and Hutchings, 2006), knocks (Midling *et al.*, 2002), and even higher frequency (>2 kHz) clicks (Vester *et al.*, 2004) have been recorded. Masking of these vocalizations may alter mate choice and inhibit breeding (Rowe and Hutchings, 2006). Some Atlantic cod populations have used the same spawning locations for centuries (Sundby and Nakken, 2008) and demonstrated homing and site-fidelity to discrete spawning areas (Green and Wroblewski, 2000; Robichaud and Rose, 2001; Wright *et al.*, 2006; Svedang *et al.*, 2007; Skjæraasen *et al.*, 2011). Such fixed site fidelity suggests that they may not avoid areas newly targeted for seismic surveys. If seismic surveying occurred at spawning sites during the pre-spawning or spawning period, it could potentially reduce spawning efficiency as some studies show elevated cortisol levels after exposure to tonal signals (Sierra-Flores *et al.*, 2015), which may further slow their recovery. Furthermore, mating behaviors may also be impacted as the communication space of Atlantic cod has been shown to be reduced when exposed to noise from vessels transiting their breeding grounds (Stanley *et al.*, 2017). It is also suspected that impulsive sounds, such as those associated with seismic surveys, now a common noise source on the Atlantic coast of Newfoundland, can interfere with communication in Atlantic cod (Sierra-Flores *et al.*, 2015).

In this paper, we assess auditory masking for Atlantic cod during a single pass-by of a realistic seismic surveying vessel operating a typical air gun array to understand the applicability of communication and listening space methods for management. The results of both the sonar and listening space equations are directly compared in terms of their reliability and ecological implications, as well as their required inputs, sensitivity to errors, and assumptions. Recommendations for the application and interchangeability of these two methods for quantifying masking in marine ecosystems, particularly for management, are also suggested.

## II. METHODS

### A. Acoustic data

Acoustic data were collected between 2 September and 31 October 2016 by Fisheries and Oceans Canada

(St. John's, Newfoundland, Canada) and JASCO Applied Sciences (Dartmouth, Nova Scotia, Canada) during a commercial two-dimensional (2-D) seismic survey off the Grand Banks, Newfoundland, Canada (Fig. 1). The received SPLs of air gun pulses were measured using a calibrated M36-V0 omnidirectional hydrophone ( $\sim -200$  dBV/ $\mu$ Pa sensitivity; GeoSpectrum Technologies Inc., Dartmouth, Nova Scotia, Canada) attached to an Autonomous Multichannel Acoustic Recorder (AMAR; JASCO Applied Sciences, Dartmouth, Nova Scotia, Canada). The AMAR was bottom-mounted at 120 m water depth at the head of Carson Canyon on Grand Banks. The AMAR was operated on a duty cycle of 7-min recordings at 32 kHz sampling rate alternating with 1-min at 375 kHz. While the deployment was over a two-month period (those data are presented in Morris *et al.*, 2018), this study used only data from a single controlled pass-by of the seismic survey vessel towing the 4880 in.<sup>3</sup> air gun array (performed by the PGS Atlantic Explorer, Petroleum Geo-Services ASA, Oslo, Norway). The air gun array passed directly overhead of the recording system (i.e., a horizontal range of 0 m), and the full range of the received SPLs during a typical transect was analyzed. The length of the seismic survey vessel's transect was 18 km.

**B. Data analysis**

To compare the two masking methods, recorded air gun pulses over the 18 km transect were analyzed, providing the range-dependent SPLs as the air gun array passed the recording system. A custom-designed program was built in MATLAB (The MathWorks, Natick, MA) that plotted the air

gun pulse locations (from the vessel's P1/90 logs), and then detected the air gun pulses, providing the per-pulse SPLs for the corresponding slant ranges (Fig. 2).

Since air guns emit impulsive noise, auditory masking was assessed based on the reverberation of the air gun noise pulse (Guan *et al.*, 2015). Masking is maximum when the pulse first arrives and gradually decreases until either the ambient SPL (i.e., ambient level) or audiogram noise floor is reached or the next pulse arrives (depending on the source-receiver range). Therefore, looking at the pulse's reverberation provides a more accurate description of auditory masking effects from the perspective of a listener and accounts for the decay of impulsive signal amplitudes with time. Therefore, we calculated the SPL for each 0.5 s bin from the pulse's first arrival. The integration time (the minimum length that a signal would need to be in order to be perceived by the listener) for Atlantic cod is unknown, so instead we based it on the length of their vocalizations—the reason being that for a call to be evolutionarily selected for, it would have to be perceivable. Atlantic cod grunts range between 159 and 514 ms (mean 232 ms;  $n = 40$ ; Stanley *et al.*, 2017), and therefore 0.5 s was chosen as it was longer than the shortest calls but still short enough to capture changes in the pulse's reverberation. The sound energy from the air gun pulse within a 0.5 s period is therefore expected to be perceivable by a cod listener.

**C. Calculating reductions in communication range**

Reductions in Atlantic cod communication range as the seismic survey vessel passed was calculated following Stanley *et al.* (2017). We refer to communication space as a

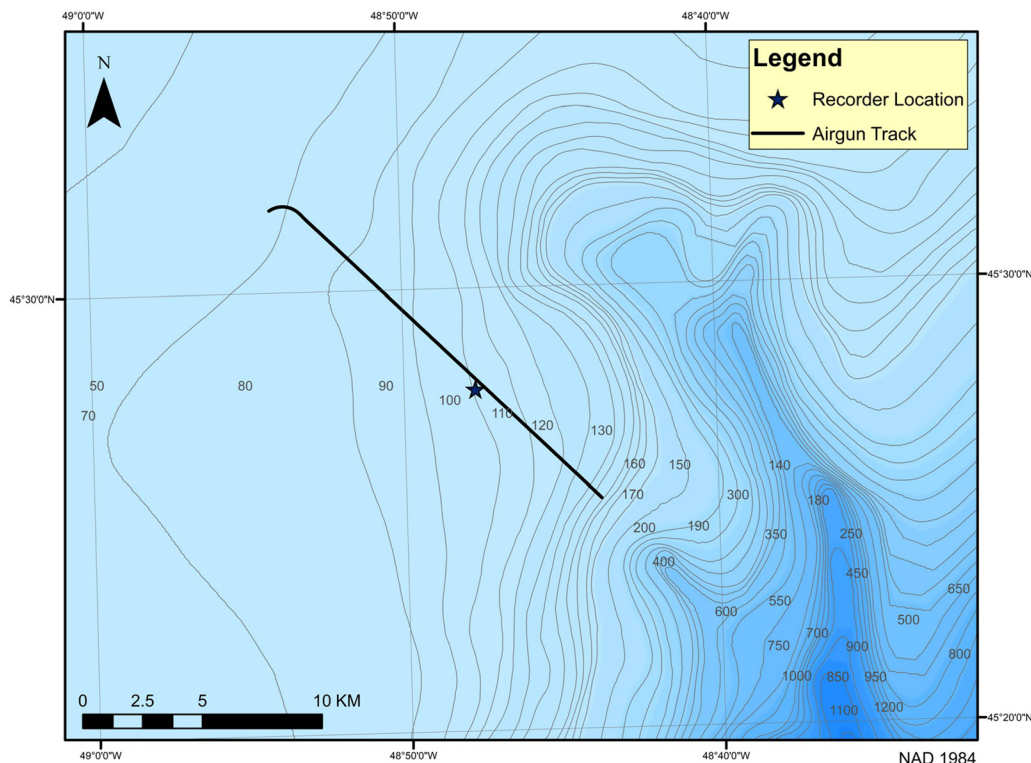


FIG. 1. (Color online) Map showing the study area where the seismic survey occurred and air gun pulses were recorded.

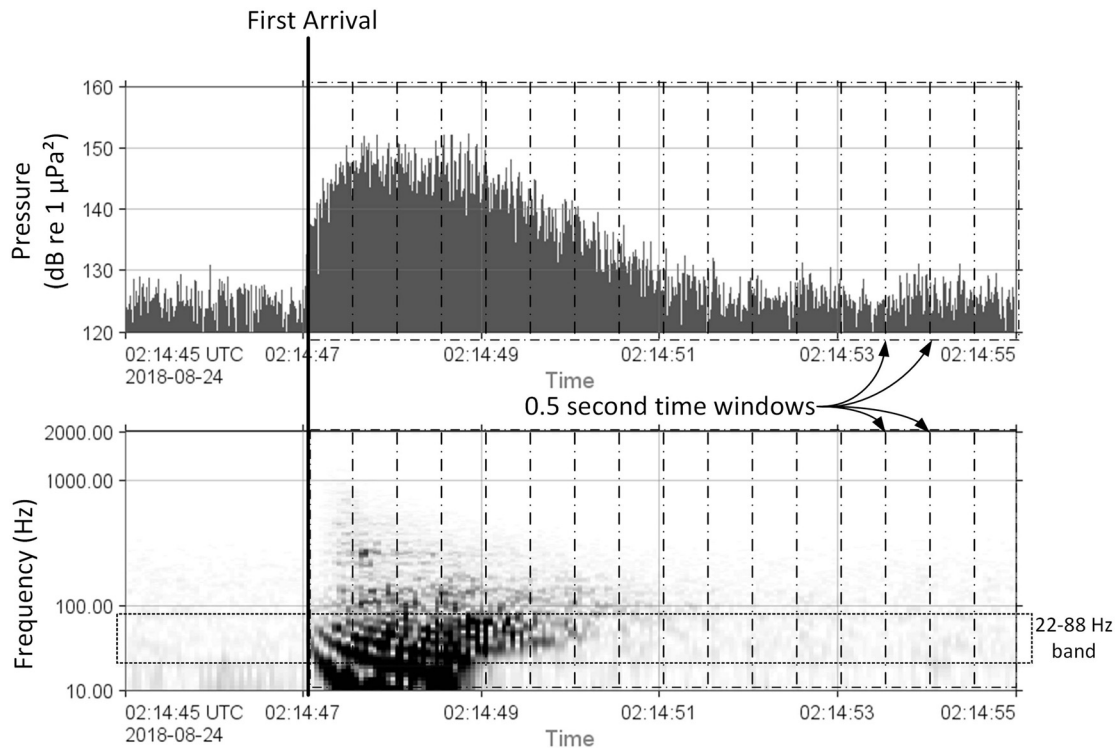


FIG. 2. Example of the automated detector process showing the 0.5 s time bins calculated from the air gun pulse’s first arrival. The masking noise levels used for the communication range reduction (CRR) and listening range reduction (LRR) equations were for the 22–88 Hz band only.

range because a single distance was calculated rather than the volume or area surrounding the animal. Similar to Stanley *et al.* (2017), we applied the same assumptions for the communication space calculations: (1) the signal was ambient-noise limited; (2) no masking release mechanisms occurred; (3) Atlantic cod exhibit omnidirectional hearing; and (4) there was an omnidirectional noise propagation field. The modified sonar equation used to calculate the communication range reduction (CRR) was

$$SE = SNR - DT,$$

therefore

$$SE = SL - N \text{Log}_{10}(r) - MSL - DT,$$

where signal excess, SE, equals zero at the limiting range for detection, SNR is the signal-to-noise ratio, SL is the source level of the fish call, MSL is the mean sound level of the environment (or audiogram limit if that is higher than the MSL in that critical bandwidth), and DT is the detection threshold (set at 15 dB; Stanley *et al.*, 2017). The source level of the Atlantic cod call was set at 127 dB re 1 μPa between 22 and 88 Hz (Nordeide and Kjellsby, 1999; Stanley *et al.*, 2017). The MSL value was the greater of either the 50th percentile ambient SPL between 22 and 88 Hz measured from a control site (located approximately 70 km away) over a 49 day period or the measured SPL of the air gun pulse for each 0.5 s after the main arrival (also between 22 and 88 Hz). The ambient level was used to determine the maximum communication

range under baseline conditions (i.e., no masking noise present).

The communication range under both masking and basement noise conditions was then calculated by finding the distance at which SE = 0, using

$$r_1 = 10^{(SL - MSL_1 - DT)/N},$$

$$r_2 = 10^{(SL - MSL_2 - DT)/N},$$

where  $r_1$  and  $r_2$  are the communication range under basement and masking noise conditions, respectively. The propagation loss coefficient,  $N$ , was calculated by curve fitting the received SPLs (between 22 and 88 Hz) from each air gun pulse with the slant range from the source (Fig. 2). Finally, the CRR (expressed as a percentage change from the basement noise conditions) for each 0.5 s time bin after the signal’s first arrival was calculated using

$$CRR(\%) = 100 \left( \frac{r_1 - r_2}{r_1} \right).$$

The CRR was calculated so as to be directly comparable to the listening range reduction (LRR).

#### D. Calculating reductions in listening range

Auditory masking based on Atlantic cod listening space was calculated following the equations from Pine *et al.* (2018), who define the LSR as

$$LSR(\%) = 100(1 - 10^{-2(\Delta/N)}),$$

where  $N$  is the same propagation loss coefficient value as used for CRR and  $\Delta$  is the difference between the basement noise level ( $MSL_1$ ) and the masking noise level (i.e., the air gun pulse,  $MSL_2$ ) at a given distance. However, we altered the equation slightly to allow for direct comparison with CRR, giving the LRR as

$$LRR(\%) = 100(1 - 10^{-\Delta/N}).$$

The product of this equation is the percentage reduction to the linear range rather than the area which the original equation provided. Unlike for the CRR, however, the basement noise level for the LSR equation was the perceived ambient level and was therefore the maximum of the cod's hearing threshold (audiogram value, taken from *Nedwell et al., 2004*) and the ambient level inside a critical bandwidth [*Pine et al., 2018*; the critical bandwidth was estimated by the full octave bands (*Stanley et al., 2017*; *Pine et al., 2018*) centered at 31.5 Hz and 63 Hz, encompassing the same energy as between 22 and 88 Hz].

### III. RESULTS

#### A. CRR

The communication range was substantially reduced at all times during the seismic survey vessel's line run (starting at 11.3 km away from the hydrophone). Generally, the reverberation of the air gun pulse in terms of masking was shorter at further ranges than when the air gun array was within 2 km of the hydrophone (Fig. 3). For example, 100%

reduction in the communication range was seen for the full inter-pulse interval of 9 s within 2 km. However, beyond 10 km, 100% CRR was observed for approximately 3 s following the pulse's first arrival, decreasing to 60% CRR after 9 s. Interestingly, CRR was not stable with range with 100% CRR occurring for up to 6 s after the pulse's first arrival at the hydrophone between 8 and 9 km, decreasing to approximately 3 s at 10.5 km, then increasing again to 5 s at 11 km. At ranges closer than approximately 2 km, 100% CRR was observed for the complete 9 s between pulses. Beyond 2 km from the air guns, conspecific communication may be possible for a short time (a few seconds since the air gun shot frequency was  $\sim 1$  shot/10 s) between air gun pulses but over a much smaller range since the communication range is still reduced by at least 60%–70%.

#### B. LRR

Reductions in Atlantic cod listening ranges gradually decreased after a maximum of 1.5 s from the first arrival of the air gun pulse. At the closest ranges (inside 500 m), the LRR was a minimum 90% between pulses (Fig. 3). This meant detection of biologically important signals may be possible for up to 5 s before the air gun pulse arrives at those ranges. Generally, the length of time between air gun pulses when that 90% LRR was exceeded gradually shortened with increasing distance from the air gun array. At the furthest distances, beyond 10 km, LRRs over 90% only lasted for 2–3 s before gradually decreasing to a minimum LRR of approximately 65% after 9 s. The output of the LRR equation appeared to better reflect the diminishing energy of

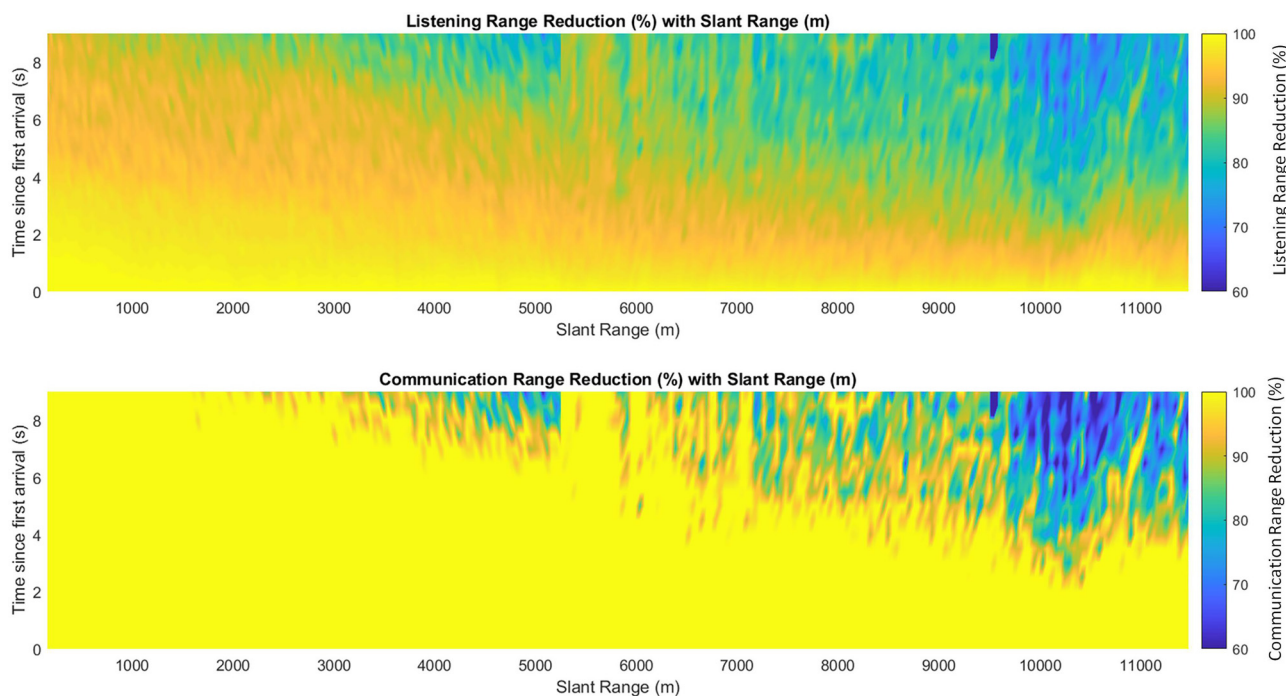


FIG. 3. (Color online) Communication and listening range reduction (%) plots as a function of both slant range (m) and the air gun pulse's reverberation (maximum 9 s until next air gun pulse arrives).

each of the multipaths of the air gun pulses than did the CRR output.

#### IV. DISCUSSION

Regardless of the method used, our results indicate substantial masking effects for Atlantic cod in between air gun pulses that will continue as long as the masking noise and cod listener are within at least 11 km. For prolonged anthropogenic activities near important habitats for species showing fixed site fidelity, the exposure and subsequent masking effects could last several months. However, the level of masking was not constant with peak CRR and LRR occurring when the air gun pulse first reached the listener (termed the direct path or first arrival), and then rapidly decreasing as the pulse's surface and seafloor reflections passed the receiver (termed multipaths) in the seconds following the first arrival.

Maximum masking effects (i.e., 100% reduction in active space) in terms of listening and communication range were, respectively, within 1.6 km and 2.0 km for the complete 9 s inter-pulse interval. Therefore, assuming a spawning aggregation of Atlantic cod is relatively stationary, the survey vessel [travelling approximately 5 knots ( $8 \text{ km h}^{-1}$ )] has the capability, in theory, to cause complete masking for at least 12 min (based on LRR) or 15 min (based on CRR). This is because at those smaller ranges, the air gun pulse's reverberation exceeds the amplitude of the cod's call and thus maintains a substantial SNR or SE. However, a key assumption of energetic-based masking assessments (such as this study) is that masking release for the receiver (including gap listening) or anti-masking strategies by the sender are not factored in, thereby potentially overstating true masking. It is also important to note that cod grunts are often repeated in some contexts and consist of repeated pulses, meaning that because impulsive signals (such as air guns) are also repeated, cod grunts may not always overlap temporally.

Fish have evolved in a noisy environment with many natural sources (such as waves and conspecific or heterospecific choruses) acting as effective maskers (Radford *et al.*, 2014). It therefore stands to reason that they have evolved to counteract naturally occurring maskers, ensuring their vocalizations can be detected over ambient noise levels. Anti-masking strategies by the sender are predominately altering the call's characteristics, such as increasing call amplitude (Lombard effect), changing the spectral characteristics of a call (for example, lowering or raising the fundamental or peak frequencies) to reduce spectral overlap, or altering the temporal dynamics of the call, for instance, increasing call rates or repetition (Radford *et al.*, 2014; Erbe *et al.*, 2016). There may also be repeating information at multiple frequencies within a call's harmonics, which occur within cod grunts. In addition, masking release at the listener may occur when the call and masking noise are coming from different directions (termed spatial release from masking, SRM) or when the masking noise is amplitude

modulated over a bandwidth much wider than the critical band of the listener (termed comodulation masking release, CMR; Erbe *et al.*, 2016). While these have been studied in marine mammals, anti-masking strategies and masking release in fish are less understood. Furthermore, the role of particle motion in sound perception in terms of masking is unknown and is a topic that future research on how sound pressure and particle motion work together in masking release should address. Notwithstanding, one study has shown that lower SNRs are required for signal-source determination when exposed to an amplitude comodulated masker than for white noise in the goldfish, *Carassius auratus* (Fay, 2011). Some fish have also demonstrated some degree of vocal plasticity in response to more short-term stimuli (as opposed to evolutionary timescales) (Radford *et al.*, 2014). For example, damselfish (Pomacentridae) alter the pulse rates of their calls when acting agonistically with conspecifics versus heterospecifics (Mann and Lobel, 1998; Parmentier *et al.*, 2010), gulf toadfish (*Opsanus beta*) decrease their call rates in response to predator presence (Remage-Healey *et al.*, 2006) and increase their call amplitudes to outcompete rival males in attracting females (Fine and Thorson, 2008), and Lusitanian toadfish (*Halobatrachus didactylus*) males shorten their calls and pulse periods at low tide (Amorim *et al.*, 2011). Very few fish are known to be able to adjust the frequency of their calls with only two freshwater gobies (*Padogobius martensii* and *Gobius nigriscans*) and Lusitanian toadfish being reported to have such capabilities (Lugli *et al.*, 2003; Amorim *et al.*, 2011; Radford *et al.*, 2014). However, based on the relative simplicity of fish calls, there may be reduced possibility for fish to immediately adjust their calls in response to anthropogenic maskers (Radford *et al.*, 2014). Also, if the call/signal is of a wider bandwidth than the masking noise, some information may be lost but not all (Clark *et al.*, 2009); however, that is less relevant in this study due to the bandwidth of the air gun pulses at close ranges and the narrow bandwidth of the cod's call.

The outputs of the two masking methods begin to diverge with increasing range with 90% LRR occurring after 6 s following the pulse's first arrival compared to 100% CRR at the same time. As the source-receiver distance increases, however, the CRR method becomes less stable than the LRR method. This is because the sonar equation by definition is directly related to the SNR of the call at some distance (thus considering masking from the sender), while the LRR is based on the relationship between noise exposure and maximum listening ranges as a function of the propagation loss slope (thus considering masking at the listener) and not the SE of a specific call based on its source level (Pine *et al.*, 2018). Therefore, when assessing masking in terms of an impulsive signal reverberation, slight pressure fluctuations in that signal's multipaths lead to more erratic changes in the CRR method.

The accuracy of either method is dependent on the input parameters. The key parameter in the simplified sonar equation is the source level of the sender's call, while for the

LRR equation the key parameter is the ratio between the masking noise level and basement level (being either the ambient level or hearing threshold). Call source levels for marine mammals and fish are species and context specific, making source level estimates highly variable (Erbe *et al.*, 2016; Pine *et al.*, 2018), particularly for mysticete cetaceans where estimated source levels of fin whale calls varied as much as 40 dB in some cases (Miksis-Olds *et al.*, 2019). However, uncertainty and biases in source level estimates due to the propagation loss model selection, input parameters, and signal processing differences between studies further increases variability in call source levels (Miksis-Olds *et al.*, 2019). The sensitivity of the CRR method to slight changes in the call source levels (see Fig. 4) is an important consideration when applying simplified sonar equations for management purposes. Audiograms also have a high degree of variability between individuals of the same species (Nedwell *et al.*, 2004), which will cause variability in the LRR method when the range is audiogram limited. For fish, audiograms are obtained in small tanks, which do not always match *in situ* conditions (Sisneros *et al.*, 2016; Hawkins and Popper, 2017). The importance of the audiogram in the listening range calculations increases in quieter environments (or when the receiver moves between habitats of differing depths or areas on or off the continental shelf, such as for Atlantic cod) when the basement ambient level is lower than the audiogram value at some critical band (Pine *et al.*, 2018). Therefore, the LRR method is not entirely dependent on the audiogram value in the same way that the sonar equation is controlled by the call source level. This increases the strength of the listening space method for species whose call source levels are poorly understood or simply unknown.

Critical bandwidths of the listener are also incorporated into the LRR method and used for the calculation of the received SNR. The exact critical bandwidths for Atlantic

cod are unknown, however, they are believed to be wider than in other vertebrates (Stanley *et al.*, 2017). As such, SNRs in this study were calculated over a 1/1 octave band filter. Directly measuring the critical bandwidths in animals is challenging, and actual measurements are often unavailable. Previous studies on Atlantic cod hearing thresholds have therefore determined critical bandwidths indirectly using the critical ratio as  $CB = 10^{CR/10}$  (Fletcher, 1940; Tavolga, 1974; Erbe *et al.*, 2016). However, this equation does not always provide the most accurate results (Erbe *et al.*, 2016). Measurement-based estimates of critical bandwidths in Atlantic cod (Buerkle, 1969; Hawkins and Chapman, 1975) do result in increasing critical bandwidths with frequency like that of a 1/1 octave band filter but slightly wider. Regardless, the LRR analysis is likely insensitive to the critical bandwidths over which SNRs are calculated because the masking noise and signal are generally wider than the critical bandwidth of the listener. Therefore, a wider band would increase the level of both the masking noise and signal, resulting in the same SNR (Pine *et al.*, 2018).

The relative usefulness of the two methods in terms of the EIA process depends on the species or ecosystem of concern. Previous studies on masking impacts have focused on communication impairment in marine mammals (Clark *et al.*, 2009; Erbe *et al.*, 2012; Hatch *et al.*, 2012). For many marine mammal species, obtaining accurate audiograms is challenging with large whales or rare species unable to be kept in captivity or adequately trained (Ridgway and Carder, 2001; Tubelli *et al.*, 2012), thus, forcing hearing thresholds to be modeled off anatomical measurements. For those species kept in captivity and trained for audiogram testing, the results typically suffer from low sample sizes and animals that have been exposed to higher noise levels than their free-ranging counterparts (i.e., extraneous noise sources associated with dolphinariums). The best information that can be gathered on free-ranging whales *in situ* is characterizing their calls and estimating source levels under certain contexts. As a result, the sonar equation for estimating communication range has had wide-spread uptake for marine mammals (e.g., Jensen *et al.*, 2009; Hatch *et al.*, 2012) and will continue to be a useful method for some marine mammals in the presence of masking noise. However, for bony fish, audiograms can be obtained from wild-caught individuals that require no training of the animal [via auditory evoked potential (AEP) audiometry or behavioural response; Hawkins and Popper, 2017], and therefore larger sample sizes can be collected at lower cost than for marine mammals in general. In those cases, the LRR method may be more appropriate.

### A. Summary and recommendations

The results from this study vary in the outputs between CRR and LSR assessments. The key difference between these two methods of assessing masking is that communication space methods consider masking from the sender, while

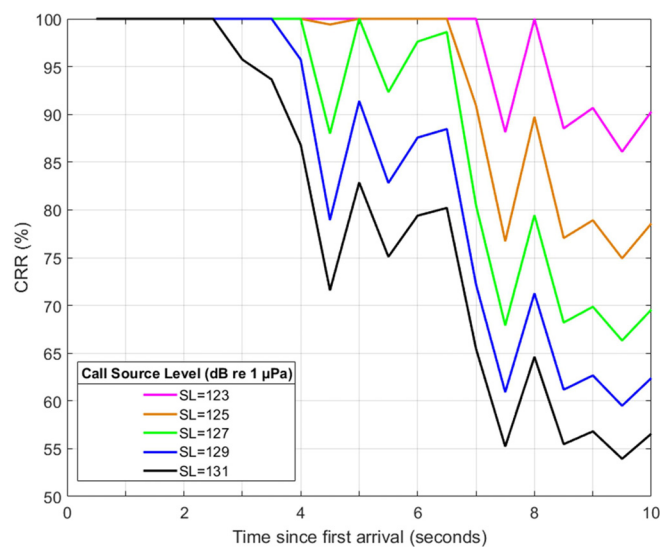


FIG. 4. (Color online) Plot showing how small changes to the source level of the Atlantic cod call influences the CRR (%).



the listening space calculation considers masking from the listener's perspective. We applied both methods to assessing an Atlantic cod call as a commercial air gun array passed a stationary receiver to investigate the applicability of either method for management. The results did show differences in the outputs with CRRs being more sensitive to slight fluctuations in sound pressures from the reverberation of the air gun pulse and estimates of the call's source level, leading to an instability not seen using the listening space method. Based on the known variability in call source levels and bandwidths between species and contexts, masking assessments based on communication space methods require care. Similarly, when the listener's hearing thresholds are well above the natural ambient noise levels in the corresponding critical band, the listening space method becomes more dependent on the listener's audiogram. This is particularly relevant for studies that consider a listener that moves between different depths and habitats in which the ambient noise levels can vary substantially. Thus, we recommend communication space methods should be used only for species whose call structures at the source and receiver's detection thresholds are well understood or when data on those species' vocalizations are more reliable than their audiograms (and the ambient noise level is low). For species

whose calls are poorly understood but whose audiograms are known (or can be reasonably justified), the listening space method is recommended (see Fig. 5 for a decision framework). Also, because the communication space method requires the use of sonar equations, they are inherently limited to vocalizations and not relevant for other biologically important signals, such as those given off by predators. Since the listening space method is assessing masking at the receiver based on changes in its perceived soundscape in the presence of masking noise, it can be applied to any biologically important signal. Therefore, we recommend listening space be used when investigating general masking effects within an ecosystem where not all species therein have established vocal behaviors or studied source levels. The listening space method can also be applied to nonvocal species since no information on the masked signal at the source is needed. For species that rely heavily on intraspecific communication over short distances (for example, breeding seasons in Atlantic cod), the communication space method provides a more conservative estimate of masking impact for impulsive signals, such as air gun pulses. However, detrimental impact from masking during spawning in some fish (such as Atlantic cod) may not be limited to impaired intraspecific communication but also

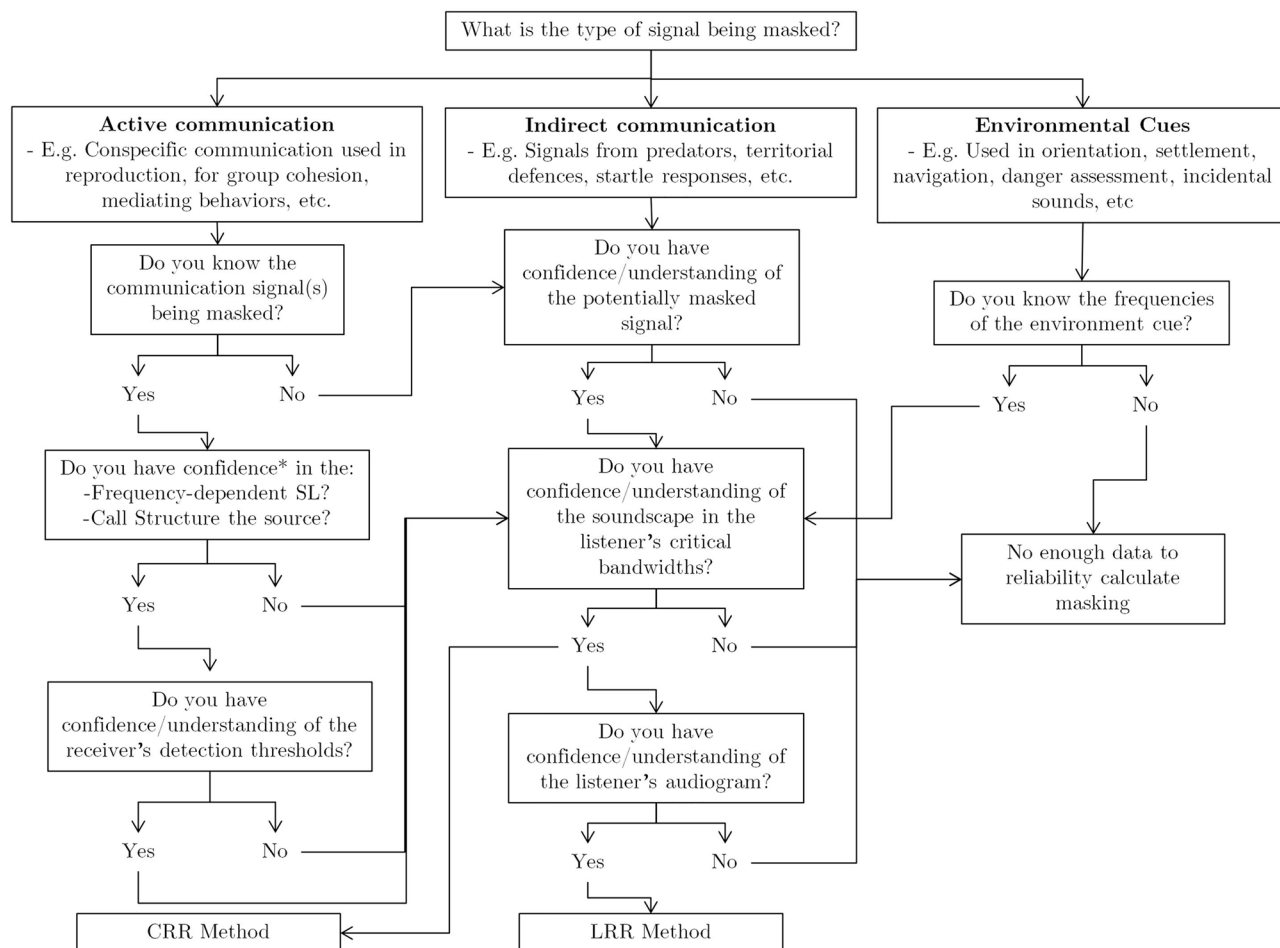


FIG. 5. Decision framework for when to apply either the CRR or LRR method to auditory masking assessments.

reduced ability to perceive threats and environmental cues. Thus, the two methods are complementary and inform EIAs in different ways.

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