Proceedings of Meetings on Acoustics

Volume 27 http://acousticalsociety.org/

Fourth International Conference on the Effects of Noise on Aquatic Life
Dublin, Ireland
10-16 July 2016

Listening for signals in seismic noise: A case study of masking in Arctic seals

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When considering the effects of noise on hearing in marine mammals, standard audiometric data are commonly applied to predict how a noise source will influence an individual or species. With regard to auditory masking, critical ratio measurements and average noise spectral density levels can be used to obtain masked threshold predictions. However, the extent to which this method is appropriate varies based on the features of the noise source in question. Temporally varying noise, such as that generated by seismic surveys, presents a significant challenge. To address this, we trained captive spotted and ringed seals to detect 100 Hz narrowband signals embedded within a background of seismic noise recorded from an operational air gun array. The masking data demonstrated that conventional masked threshold predictions were least accurate when the noise exhibited the greatest amplitude fluctuation in time. This study addresses the important issue of masking outside of the laboratory, and provides much needed information about when it is appropriate to use average noise levels and critical ratio data to predict masking in real environments. Our results can inform best management practices for evaluating the effects of noise on Arctic seals and other marine mammals.

Published by the Acoustical Society of America

 [DOI: 10.1121/2.0000243]

1. INTRODUCTION

Climate warming and human development are transforming Arctic environments. Ice-living seals in the region face a multitude of resulting threats, including the potential for adverse behavioral or auditory effects caused by increasing levels of human-generated noise. The possible deleterious effects of impulsive noise sources—such as seismic air guns or impact pile-driving operations—are usually evaluated with regard to temporary or permanent shifts in auditory sensitivity at high exposure levels. However, the potential for auditory masking typically extends over a much larger area surrounding a given noise source than does the potential for auditory injury (see, *e.g.*, Richardson *et al.*, 1995). More individuals may therefore experience masking from impulsive noise sources than experience noise-induced hearing loss. While impulsive noise is characterized by a sharp onset with rapid rise and fall times, propagation and reverberation of low-frequency components of air gun pulses across tens to thousands of kilometers can increase background noise levels even during the intervals between pulses (Greene and Richardson, 1988; Guerra *et al.*, 2011; Nieukirk *et al.*, 2012; Guan *et al.*, 2015; Nowacek *et al.*, 2015). Accurate predictions of auditory masking for seals, who are sensitive to such low-frequency sound, are thus necessary to inform effective noise management practices in an increasingly industrialized Arctic.

Typical studies of auditory masking involve detailed measurements of hearing (tone detection thresholds) in the presence of noise (spectrally flattened or “white” noise). As a first approximation, standard audiometric data (*i.e.*, critical ratio measurements) can be used to predict how noise will influence hearing. To estimate the quietest detectable level of a tonal signal given certain noise conditions, the critical ratio can be added to the spectral density level of the noise at the same frequency. However, this conventional method may not generate valid estimates of masking in the case of dynamic (time-varying) impulsive noise. The simple audiometric signals and maskers used to measure hearing in the laboratory differ substantially from biological signals (such as vocalizations) and noises (such as seismic air guns) that are encountered by marine mammals in the real world. Furthermore, conventional methods for predicting masking are often based on average noise levels over the duration of the target signal, which may not be appropriate for noises that vary significantly in time. Prior work has shown that the classic application of critical ratio data to predict masking in realistic listening scenarios is valid in some cases and inaccurate in others (see, *e.g.*, Erbe and Farmer, 2000; Erbe, 2002; Jensen *et al.*, 2009; Branstetter *et al.*, 2013; Dooling *et al.*, 2013; Cunningham *et al.*, 2014). The extent to which this conventional method can be reasonably applied to evaluate hearing in marine mammals in the presence of impulsive noise remains unclear.

The need to quantify masking by impulsive noise is relevant due to widespread geophysical exploration in Arctic regions. As there are presently no data describing the simultaneous effects of impulsive noise on hearing (masking) in seals, our objectives in this study were to 1) measure the masking effect of impulsive noise on Arctic seals using psychoacoustic methods, and 2) compare results to predictions based on critical ratio measurements obtained with tonal signals and broadband, flat-spectrum maskers.

2. QUANTIFYING MASKING IN THE PRESENCE OF IMPULSIVE NOISE: AN EXPERIMENTAL APPROACH

A. EXPERIMENTAL PARADIGM

To investigate the extent to which impulsive noise constrains hearing in seals, we conducted an auditory go/no-go procedure with trained spotted (*Phoca largha*) and ringed seals (*Pusa hispida*). One individual of each species participated in this experiment; both subjects had extensive prior experience with behavioral tests of hearing. Additional details regarding the test subjects (spotted seal *Tunu* NOA0006674; ringed seal *Nayak* NOA0006783) and the psychophysical paradigm are available elsewhere (Sills *et al.*, 2014; 2015; In Review).

Subjects were trained to report the detection of low-frequency target signals presented during different time intervals of a seismic noise background. *Target signals* were 500 ms, narrowband frequency-modulated sweeps centered at 100 Hz [10% bandwidth (95-105 Hz) and 5% linear rise and fall times (25 ms ramps)]. *Maskers* were calibrated recordings of seismic noise obtained close to (1 km) and far from (30 km) an operational air gun array in the Chukchi Sea (courtesy of Shell Offshore, Inc.; for details see Patterson *et al.*, 2007). Samples recorded from two distances were used as maskers in this experiment because propagation away from the source affects both the time and the frequency structure of the noise, as evident in Fig. 1. The seals learned to ignore the seismic noise masker projected on every test trial, and to report a detection only when perceiving the target signal embedded in the noise background. On any given trial, the low-frequency target signal the seals were listening for could occur either in the *onset*, the *intermediate*, or the *terminal* interval of the noise (see Fig. 1). These intervals represented either the impulsive (coincident with pulse onset) or the reverberant (1 or more seconds after the initial pulse) portion of the seismic noise.

Auditory stimuli were projected from a Naval Undersea Warfare J-11 transducer (Newport, RI, USA) in the test enclosure. The level of each masker was invariant throughout the experiment. Signal-to-noise ratio (SNR) was varied from trial to trial by adjusting the level of the target signal. This enabled determination of percent correct detections at various SNRs for signals within each of the three intervals (onset, intermediate, and terminal) of the two seismic maskers (1 and 30 km). Signal-to-noise ratios were determined at the 50% correct detection threshold in the 100 Hz 1/3-octave band for each of the six testing conditions. These values were compared to masked threshold predictions based on critical ratio measurements obtained previously at 100 Hz for the same subjects (Sills *et al.*, 2014; 2015). SNR offsets from predicted were calculated by subtracting predicted threshold from measured threshold.

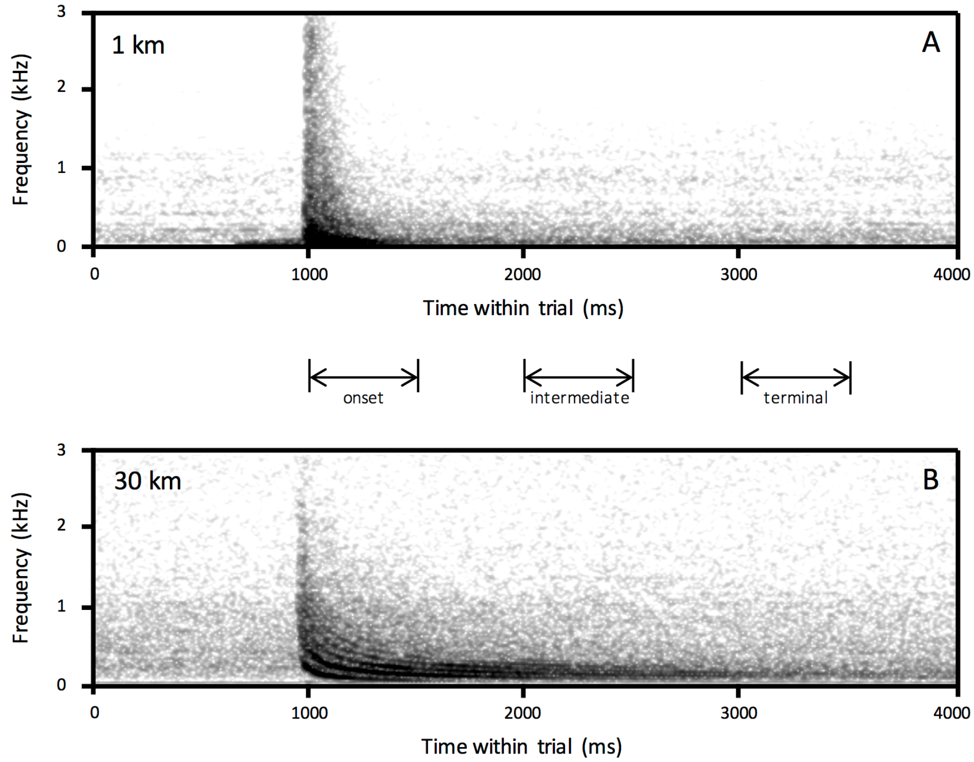

Figure 1. Shown here is the spectrogram for a seismic air gun array recorded in the Chukchi Sea at a relatively close distance (~ 1 km from the source, panel A), and the spectrogram for the same air gun array recorded at a farther distance (~ 30 km from the source, panel B). Spectrogram analysis settings were as follows: sampling rate 44.1 kHz; Hann window; FFT size 2048 (filter bandwidth 31 Hz); overlap 90%. To account for temporal variability in the noise, we quantified the masking of signals presented during three discrete time intervals of these maskers. Drawn between the spectrograms are markers denoting the portions of the 4-second trial during which a signal could potentially occur (labeled as the onset, intermediate, and terminal intervals of the noise). Masking noise was presented on every trial; noise alone was presented on 50% of test trials (signal-absent trials), and target signals were presented on 50% of test trials (signal-present trials). The target signal could occur on any signal-present trial in either the onset, the intermediate, or the terminal interval.

B. EXPERIMENTAL FINDINGS

This psychophysical paradigm involved the parsing of a single seismic pulse into multiple noise maskers, acknowledging the dynamic masking potential of this type of noise. Furthermore, the use of seismic noise recorded at different distances from the source recognizes that the sound field surrounding an air gun operation is variable both temporally and spatially. This unique methodology enabled us to conduct an experimental evaluation of masking by seismic pulses, and to assess the performance of conventional methods of estimating masking.

Both subjects exhibited reductions in hearing sensitivity in the presence of the projected seismic noise. By comparing our experimental results to masking predictions based on conventional methods, we found that we could accurately predict the extent of masking in the latter two intervals (sensitivity ≈ predicted in the intermediate and terminal intervals of the impulse), which represent the reverberant portion of the noise. However, conventional methods failed to predict the extent of masking in the initial interval of the noise (sensitivity > predicted in the onset portion of the impulse). For tonal signals overlapping in time with the initial impulse, critical ratio predictions yielded overestimates of the extent of masking. This result is not unexpected, considering the large amplitude variation in the noise during the onset interval. The significant release from masking observed (up to 23 dB) can be attributed to dip listening (Buus, 1985) by the seals. To investigate this phenomenon, we examined the amplitude fluctuations in the noise background with more refined temporal analysis.

C. TIME WINDOW ANALYSIS

We had measured relative noise amplitude and received SNR at threshold for both the 1 km and the 30 km maskers (in the three masker intervals) within the relevant 100 Hz 1/3-octave band. Here, noise amplitude and SNR were further analyzed for each condition using sliding time windows with different durations (50 – 500 ms, in 50 ms increments). We found that when noise fluctuated significantly in time (*i.e.*, during the onset interval), the analysis duration strongly affected measured noise amplitude, and thus made threshold predictions less accurate. In all intervals, predicted SNR at threshold was exceeded by received SNR at threshold for at least some of the analysis durations used, indicating that signal detection was possible. This incremental time window analysis explains how the seals detected the signal hidden in the onset intervals of both maskers, even when masking predictions based on longer term (500 ms) averages indicated that the signal was too quiet to be heard. This finding suggests that masking predictions could be improved by measuring signal-to-noise ratios within shorter time windows than the full 500 ms signal duration, regardless of expected temporal processing abilities (Sills *et al.*, In Review).

3. CONCLUSION

This study provides insight into the simultaneous effects of impulsive noise on hearing in marine mammals. Although impulsive noise is typically considered with regard to noise-induced hearing loss at close ranges, we found that transient noise can cause auditory masking in seals—and likely other marine mammals—even relatively close to the source. In the reverberant portions of the noise that follow the initial pulse, critical ratio data can often be used to accurately predict zones of masking or communication ranges. However, when noise amplitude fluctuates significantly in time (for example during the onset of an air gun pulse), listeners can apparently detect signals within brief amplitude dips or quiet periods in the noise. In this case, predictive ability can be improved by considering SNRs measured in time windows that are shorter than the full signal duration. This result indicates that it is not always sufficient to consider noise averages when evaluating realistic acoustic environments, and that conventional methods provide conservative estimates of auditory masking. Because sound field variability is important, more detailed analyses of signals and noise may be required when accurate masking predictions are necessary. Future psychoacoustic studies with marine mammals are needed to examine auditory masking in realistic scenarios, such as those featuring complex signals paired with complex masking noise. Additionally, studies using controlled amplitude-modulated noise are needed to further investigate the phenomenon of dip listening in the presence of transient noise. These findings are relevant to marine mammals other than seals, and additional types of impulsive noise in the marine environment, such as impact pile-driving.

ACKNOWLEDGMENTS

This work was conducted with the permission of the National Marine Fisheries Service (research permits 14535 and 18902), the Ice Seal Committee, and the Institutional Animal Care and Use Committee at the University of California Santa Cruz. This research was funded by the International Association of Oil and Gas Producers, through the E&P Sound and Marine Life Joint Industry Programme [award 22-07-23]. The authors gratefully acknowledge M. Macrander of Shell Offshore, Inc. for access to the air gun pulse data sets and S. Blackwell of Greeneridge Sciences, Inc. for providing details regarding the characteristics of received pulses in the field. A. Rouse of SEA, Inc. developed the custom LabVIEW virtual instrument used in the seismic masking experiment. K. Cunningham and R. Sills provided thoughtful suggestions about time window analysis. Finally, we thank the entire research team at the Pinniped Cognition and Sensory Systems Laboratory at UC Santa Cruz for making this project possible.

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