Aquatic Mammals 2018, *44*(3), 239-243, DOI 10.1578/AM.44.3.2018.239

Short Note

An Acoustic Scene Perspective on Spatial, Temporal, and Spectral Aspects of Marine Mammal Behavioral Responses to Noise

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Overview

Considering contextual factors in sound exposure scenarios when evaluating the probability and severity of behavioral responses of marine wildlife to sound is critically important. There is an increasingly strong scientific basis supporting the role of contextual variables and the need to consider these implications in regulatory assessments of potential impacts. Recent results from experimental and observational studies of behavior and response in marine mammals (e.g., Goldbogen et al., 2013; Henderson et al., 2014; Pirotta et al., 2015) reveal the integral role of context (Ellison et al., 2012). Ellison et al. (2012) articulated the importance of considering contextual response parameters in evaluating potential behavioral responses observed in the field, provided a timely formulation for the interpretation and evaluation of previous research, and proposed specific methodological and analytical advances for future studies. We present here an acoustic scene perspective on behavioral response founded on the seminal work of Bregman (1990), and informed by the motivation-structural rules of Morton (1977). This integrated approach relies on two key quantitative spatial metrics: (1) proximity and (2) encroachment. *Proximity* is the measured range between an individual and a sound source. *Encroachment* is the rate of change in proximity. These two parameters describe spatial-contextual aspects of sound exposure scenarios which are known or likely to play an important role in mediating the potential for behavioral response across many taxa. Their introduction enables a more robust evaluation of sound exposure scenarios and provides a conceptual template with directly testable hypotheses that can be integrated into the design of behavioral response studies and applied to the analysis of existing data in both research and regulatory contexts.

Spatial proximity to a noise source in realistic field conditions can be perceived via several underlying parameters related to signal characteristics, including propagation loss of high frequencies, temporal changes in signal structure associated with multi-path sound transmission, and spectral complexity. These parameters indicating proximity have been demonstrated to mediate behavioral responses to sound in a variety of taxonomic groups (e.g., Holland et al., 2001; Pohl et al., 2012). Richardson et al. (1985) noted that faster vessels produced greater reactions than slower vessels (nominally a greater encroachment). Bowles et al. (1994) developed a reorientation score metric that incorporated relative bearing (but not distance) between a noise source and an animal receiver. Relative spatial orientation metrics have also been applied to interactions of migrating humpback whales (*Megaptera novaeangliae*) and seismic airgun activity (Dunlop et al., 2015). Similarly, Pirotta et al. (2015) found that boat activity was associated with a reduction in foraging effort by bottlenose dolphins (*Tursiops truncatus*), whereas noise level alone had no effect. Wensveen et al. (2015) assessed potential behavioral responses of long-finned pilot whales (*Globicephala melas*) to varying sound exposure levels by modeling their spatial-temporal interactions with an approaching sound source. Lalas & McConnell (2016) attempted to investigate the effect of seismic survey sounds on New Zealand fur seal (*Arctocephalus forsteri*) distribution. While unable to discern a response to seismic noise, they concluded that the source vessel and its towed gear produced behavioral responses.

More recently, Ellison et al. (2016) modeled the potential for aversion to disturbance by bowhead whales (*Balaena mysticetus*) migrating past a variety of industrial noise sources, with the level of aversion proportional to the received level. The methodology employed in that study and attendant discussion of contextual issues directly informs the approach derived here in terms of evaluating the spatial metrics of the potential for a behavioral response (hereafter, behavioral response potential).

Ellison et al. (2012) suggested that diverse spatial, temporal, and spectral relations between noise sources and marine mammals relevant to the perception of proximity be quantified in assessments of behavioral response to exposure. Herein, we explicitly address the dynamic physical metrics that are primarily related to the spatial parameters of proximity (nearness) and encroachment (relative rate of separation) that are needed to assess the relation of observed behavior to contextual aspects of the exposure. As noted above, however, variability in relative spatial orientation between sources and receivers has both temporal and spectral implications on received noise exposure which can provide information that can influence potential behavioral response probability. The intent here is that these temporal and spectral components of the associated acoustic field be informed in application by choice of either observed data or appropriate modeling techniques.

Exposure Context in Light of the Acoustic Scene

In his comparison of vision versus audition, Bregman (1990) highlighted the ability of the mammalian brain to recognize object size without regard to the distance from the observer. By association, he fosters the distance clues offered by the presence or absence of timbre in vocal communication, which he argues lay the perceptual groundwork for the use of acoustic spectrum in assessing distance. Similar perceptual and cognitive processes logically occur, or may in fact be enhanced, in animals that rely centrally on underwater sound for navigation and spatial orientation. Much like humans can distinguish between a faint rumble of thunder from kilometers away and an equivalently loud whisper from meters away, whales can likely discern noise from nearby wave action to that from a distant earthquake even at comparable received levels. This ability likely relies on the context of the medium's effect on sound transmission and adaptive and experiential aspects of auditory perception that are tuned to this physical reality—that is, animals can presumably interpret characteristics of sound sources such as proximity and relative motion given their experience with how the environment influences sound.

In his development of motivation-structural rules for acoustic communication systems, Morton (1977) focused particularly on proximity and enhanced "spectral harshness" (p. 864) as key contextual factors that influence the salience of signals to receivers and their associated behavioral response potential. In essence, range-dependent effects, such as the presence of multiple sound paths or reductions in the presence of high-frequency sound components due to frequency-specific sound absorption, likely enable animals to acoustically assess source distance independent of, or in conjunction with, received level. Thus, both the perceived level and spectral content, in addition to the movement of the sound source relative to the receiver, provide significant clues about the distance to and general nature of the sound source.

Proximity and Encroachment Algorithm

We developed an algorithm (Equation 1) to estimate the potential for behavioral response (B) that incorporates the spatial and temporal dynamics of exposure-response scenarios central to the acoustic scene concept—specifically, as they relate to the measurable variables of proximity and encroachment.

The proximity term is the instantaneous range (R) from the source to the animal. The encroachment term is Range Rate (RR), defined as the time (t) derivative of the range (dR/dt). To bound the initial range of a proximity effect, we propose setting a Proximity Constant (PC) to the range at which animal disturbance to exposure is moderate to minimal (as in Richardson et al., 1985; Bowles et al., 1994; Wensveen et al., 2015). The Range Rate constant (RC) is defined by the condition when only the animal is moving and the sound source is stationary. RC is thus nominally set to a typical animal swim speed. The algorithm is therefore applicable to both stationary and moving source scenarios. The values of PC and RC will clearly vary among scenarios and, in practice, should be informed by previous observations and operant conditions of animals and sound sources.

We combine these terms in the following nondimensional form:

$$B = PC/R - RR/RC \qquad (1)$$

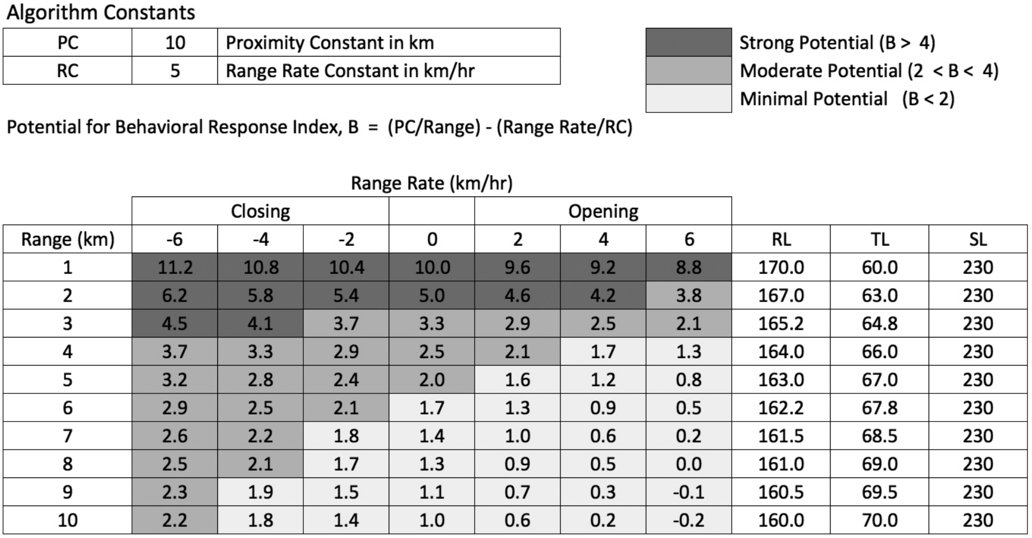
In applying this algorithm, it is necessary to establish the relation of these new metrics to the spatial and temporal characteristics of the sound field of the source. This time-varying sound field is the component of the acoustic scene to which the animal is exposed and to which it may respond behaviorally. Thus, for a given sound source such as an airgun seismic array, we estimate the temporal (time, t) and received sound level (RL) of a given airgun shot at the location of the animal. The proximity term, R, at any time (t) then becomes a surrogate for these values if the source location, source level, and transmission loss (TL) are known. Thus,

$$RL(R, t) = SL\text{-}TL(R, t) \quad (2)$$

To maintain the general applicability of this approach to a wide selection of scenarios, the spatial and temporal features of the sound field, including effects such as absorption and multipath transmission, must be assessed either through modeling appropriate to the scenario or actual recorded values. We illustrate the algorithm here in a parametric example using a simple spreadsheet format (Figure 1) for a common source configuration, that of a notional towed airgun array, SL = 230 dB re 1 µPa at 1 m, operating in continental shelf waters at a speed of 6 km/h. From Equation 1, the behavioral response potential metric, B, is evaluated at discrete ranges from 1 to 10 km, and Range Rate steps from -6 km/h to +6 km/h. In this example, the Range Rate constant (RC) is set at 5 km/h, corresponding to the average bowhead whale migration speed used in Ellison et al. (2016), and the Proximity Constant (PC) is set at the range at which RL = 160 dB re 1 µPa—10 km in this example. The simplified transmission loss calculation applied in this example assumes spherical spreading to 1 km and cylindrical spreading thereafter.

The terms "Closing" and "Opening" in Figure 1 refer to the conditions in which the Range Rate is decreasing or increasing, respectively. The effect of these two conditions is that the distance between the source and animal is either decreasing or increasing, with the value of the term reflecting how fast the distance is changing. As evidenced by the table's asymmetry around a Range Rate of 0 km/h, animals have a higher behavioral response potential at higher vessel approach (closing range) speeds. The predicted behavioral response potential decreases further as the source moves away (opening range). Higher-speed vessel approaches have been repeatedly shown to produce stronger reactions than slow approaches (e.g., Richardson et al., 1990; Williams et al., 2002)

In this example, we assumed strong, moderate, and minimal potential for disturbance at $B > 4$, $2 < B < 4$, and $B < 2$, respectively. This discrete division into three levels of disturbance is illustrative and somewhat subjective, and is informed in this example by the discussion of behavioral severity scoring in Ellison et al. (2016). The use of RL = 160 dB re 1 µPa as a proxy for initiating a behavioral response is supported as both a recognized field observation value for initial behavioral response for a number of relatively well-studied species (e.g., Miller, 2012; Antunes et al., 2014) and as a common regulatory threshold proxy for behavioral disturbance. However, data from observations of specific sources in some species and contexts indicate that values other than



Algorithm Constants

PC	10	Proximity Constant in km
RC	5	Range Rate Constant in km/hr

■	Strong Potential (B > 4)
▨	Moderate Potential (2 < B < 4)
□	Minimal Potential (B < 2)

Potential for Behavioral Response Index, B = (PC/Range) - (Range Rate/RC)

	Range Rate (km/hr)									
	Closing				Opening					
Range (km)	-6	-4	-2	0	2	4	6	RL	TL	SL
1	11.2	10.8	10.4	10.0	9.6	9.2	8.8	170.0	60.0	230
2	6.2	5.8	5.4	5.0	4.6	4.2	3.8	167.0	63.0	230
3	4.5	4.1	3.7	3.3	2.9	2.5	2.1	165.2	64.8	230
4	3.7	3.3	2.9	2.5	2.1	1.7	1.3	164.0	66.0	230
5	3.2	2.8	2.4	2.0	1.6	1.2	0.8	163.0	67.0	230
6	2.9	2.5	2.1	1.7	1.3	0.9	0.5	162.2	67.8	230
7	2.6	2.2	1.8	1.4	1.0	0.6	0.2	161.5	68.5	230
8	2.5	2.1	1.7	1.3	0.9	0.5	0.0	161.0	69.0	230
9	2.3	1.9	1.5	1.1	0.7	0.3	-0.1	160.5	69.5	230
10	2.2	1.8	1.4	1.0	0.6	0.2	-0.2	160.0	70.0	230

Figure 1. Parametric spreadsheet evaluation of behavioral response potential, B, for a marine mammal encounter with a moving sound source, evaluated at discrete ranges from 1 to 10 km, and Range Rate steps from -6 km/h to +6 km/h.

160 dB may be appropriate (e.g., Blackwell et al., 2015; Dunlop et al., 2017).

Discussion

We provide a generalized but explicit quantitative method for parameterization of the key contextual spatial and temporal elements of noise exposure. Our algorithm considers both proximity and encroachment as primary determinants of the potential for behavioral response. This parameterization is consistent with the well-established and logical concept of the acoustic scene (Bregman, 1990), as well as motivation-structural rules (Morton, 1977). The parametric form of our method readily leads to the development of hypotheses that can be tested empirically, as well as guidance for the design and evaluation of experiments, by proffering a spatial-temporal framework for categorizing observational metrics by time and distance. Further successful development and application of the algorithm requires targeted research that specifically addresses the perceptual and cognitive features of the underlying acoustic scene such as the insightful evaluation of Pirotta et al. (2015). Subsequent studies may include captive studies similar to studies of acoustic stream recognition in songbirds (Hulse et al., 1997), as well as field experimental and observational studies that evaluate behavioral response as a function of various exposure contexts (e.g., Goldbogen et al., 2013; Wensveen et al., 2015). These studies need to include robust quantification of multidimensional contextual aspects of sound exposure, including visual components at short range, as well as empirical associations between spectral content (acoustic), range, and relative motion, along the lines of a number of recent studies (Dunlop et al., 2015; Webb & Gende, 2015; Fregosi et al., 2016; Harris et al., 2017).

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