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A New Context-Based Approach to Assess Marine Mammal Behavioral Responses to Anthropogenic Sounds

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Abstract: *Acute effects of anthropogenic sounds on marine mammals, such as from military sonars, energy development, and offshore construction, have received considerable international attention from scientists, regulators, and industry. Moreover, there has been increasing recognition and concern about the potential chronic effects of human activities (e.g., shipping). It has been demonstrated that increases in human activity and background noise can alter habitats of marine animals and potentially mask communications for species that rely on sound to mate, feed, avoid predators, and navigate. Without exception, regulatory agencies required to assess and manage the effects of noise on marine mammals have addressed only the acute effects of noise on hearing and behavior. Furthermore, they have relied on a single exposure metric to assess acute effects: the absolute sound level received by the animal. There is compelling evidence that factors other than received sound level, including the activity state of animals exposed to different sounds, the nature and novelty of a sound, and spatial relations between sound source and receiving animals (i.e., the exposure context) strongly affect the probability of a behavioral response. A more comprehensive assessment method is needed that accounts for the fact that multiple contextual factors can affect how animals respond to both acute and chronic noise. We propose a three-part approach. The first includes measurement and evaluation of context-based behavioral responses of marine mammals exposed to various sounds. The second includes new assessment metrics that emphasize relative sound levels (i.e., ratio of signal to background noise and level above hearing threshold). The third considers the effects of chronic and acute noise exposure. All three aspects of sound exposure (context, relative sound level, and chronic noise) mediate behavioral response, and we suggest they be integrated into ecosystem-level management and the spatial planning of human offshore activities.*

Keywords: behavioral context, noise, received level, signal-to-noise ratio

Un Método Nuevo, Basado en el Contexto, para Evaluar Respuestas de Mamíferos Marinos a Sonidos Antropogénicos

Resumen: *Los efectos agudos de los sonidos antropogénicos (como los provenientes de sonares militares, desarrollo energéticos y construcciones cercanas a la costa) sobre mamíferos marinos han recibido considerable atención internacional de parte de científicos, reguladores e industriales. Más aun, hay creciente reconocimiento y preocupación sobre los efectos crónicos potenciales de las actividades humanas (e.g., navegación). Se ha demostrado que los incrementos de la actividad humana y del ruido pueden alterar el hábitat*

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de mamíferos marinos y potencialmente enmascarar la comunicación de especies que dependen de sonidos para buscar pareja, alimentarse, evitar depredadores y navegar. Sin excepción, las agencias reguladoras que han evaluado y manejado los efectos del ruido sobre mamíferos marinos solo han atendido los efectos agudos del ruido sobre la audición y la conducta. Más aun, se han basado en una sola medida de exposición para evaluar efectos agudos: el nivel de sonido absoluto recibido por el animal. Hay evidencia de peso de que otros factores, diferentes al nivel de sonido recibido, incluyendo el estado de los animales expuestos a sonidos diferentes, la naturaleza y novedad del sonido y las relaciones espaciales entre la fuente del sonido y los animales receptores, afectan fuertemente a la probabilidad de respuesta. Se requiere de una evaluación más integral que considere el hecho de que factores contextuales múltiples pueden afectar la manera en que los animales responden a ruido tanto agudo como crónico. Proponemos un método compuesto de tres partes. La primera incluye la medición y evaluación de las respuestas conductuales basadas en el contexto de mamíferos marinos expuestos a sonidos diversos. La segunda incluye medidas de evaluación nuevas que enfatizan los niveles de sonido relativo (i.e., la relación señal-ruido de fondo y el nivel por encima del umbral de audición). La tercera considera los efectos de la exposición a ruido crónico y agudo. Los tres aspectos de la exposición a sonidos (contexto, nivel de sonido relativo y ruido crónico) median la respuesta conductual, y sugerimos que deben ser integrados al manejo a nivel de ecosistema y en la planificación espacial de actividades humanas cerca de las costas.

Palabras Clave: contexto conductual, nivel recibido, relación señal-ruido, ruido

Introduction

For the last several decades, there has been considerable interest in the science and management of the effects of anthropogenic sounds on marine life (e.g., National Research Council 1994, 2005; Southall et al. 2007). Anthropogenic sounds include sounds that are produced purposely (i.e., signals, such as sonar pulses or seismic airgun impulses) or as a biproduct of some activity (e.g., noise, such as from ship engines or pile driving). For simplification, we use the term *sound* to refer to any acoustic signal or noise produced by an anthropogenic activity. Most attention has focused on the acute effects of military sonar on marine mammals in response to stranding events that occur during military sonar-training operations (e.g., D'Amico et al. 2009). The potential effects on marine mammals of other acute sound-producing activities (e.g., oil and gas exploration, offshore construction, and the deployment of offshore energy facilities such as wind farms) have also been assessed. In addition, there has been increasing recognition of the extent to which some of the more ubiquitous noise sources, such as ships, can either individually or cumulatively mask communication signals of marine mammals (Clark et al. 2009).

There has been a related realization that overall increases in oceanic background noise from chronic activities can alter acoustic habitats over large regions in ways that may be detrimental to marine mammals that rely on sound for basic life functions (Andrew et al. 2002; McDonald et al. 2008). A more comprehensive assessment of the effects of human noise in the ocean (e.g., Hatch & Fristrup 2009) is consistent with evolving U.S. and European management of marine ecosystems (e.g., EU Marine Strategy Framework Directive 2008; White House Executive Order 2010).

Agencies mandated to regulate environmental effects of human activities have long been required to assess and minimize potential adverse effects of noise from certain activities. To date, adverse effects of chronic sound sources (e.g., commercial shipping) at the level of individuals, populations, species' habitats, or ecosystems have not been incorporated into management decisions. Furthermore, almost all regulatory and impact-assessment approaches to date have relied on one acoustic metric for predicting effects of noise exposure: the estimated absolute received sound pressure level. The received-sound-level approach is most readily described by the zones of influence concept (Richardson et al. 1995). This concept conveys the potential severity of effects from sound exposure with a spatial representation of concentric regions (i.e., zones of influence) centered on a sound source, such that effects diminish as range from the sound source increases and received sound level decreases. These zones are typically interpreted as a hierarchy of assumed severity of effect that is based wholly on the received sound level (i.e., effectively a dose–response approach to assessment).

Focusing exclusively on the amplitude of the received sound ignores a diverse suite of environmental, biological, and operational factors (i.e., context) that may affect both the perception of received sounds and complex behavioral responses that they may invoke. There is compelling evidence that a variety of factors can determine the form, probability, and extent of an animal's response to sound. Accounting for these factors will require a fundamental shift in the current approach used to manage anthropogenic sounds in the ocean. This will not be simple given the many possible situations in which animals are exposed to sound, the limited understanding of factors mediating behavioral response for most species, and long-standing challenges in quantifying the biological significance of behavioral responses (National Research Council 2005). However, incorporating context into behavioral-response assessment is a regulatory change deemed necessary by both the scientific community (Southall et al. 2007) and sound-producing and regulatory agencies within the U.S. federal government (Southall et al. 2009).

Context-Based Behavior

Southall et al. (2007) reviewed the existing data on hearing and the effects of anthropogenic sounds on marine mammals. They used information they gathered for their review and data on effects of sound on terrestrial species to derive noise-exposure criteria, but also acknowledged gaps in data on the hearing capacity of many species, including all mysticete cetaceans. They concluded there are sufficient data to establish initial quantitative exposure criteria for direct physical effects (injury). However, they also concluded that a comparable approach to assessing behavioral effects based solely on received sound level was not warranted. In an effort to evaluate behavioral responses to sound more systematically, Southall et al. (2007) derived a qualitative, 10-step index for the severity of behavioral response (our abbreviated version is in Table 1) on the basis of the observed physical magnitude of the response (e.g., minor change in orientation, change in respiration rate, fleeing the area) and its potential biological significance (e.g., cessation of vocalizations, abandonment of feeding, separation of mother and offspring). When this severity index was applied to reports of behavioral observations relative to the received sound level, Southall et al. (2007) found that the exposure sound level (e.g., the zones-of-influence or dose–response approach) fails to reliably predict the probability of identifiable behavioral responses. They also noted that behavioral responses are strongly affected by the context of the exposure and by the animal's experience, motivation, and conditioning. These factors may have an equal or greater importance than sound level for predicting the probability of the type or severity of a response.

Three of the most obvious contexts that affect responses to sound are the relative spatial and temporal relation of the sound source and receiving animal, behavior learned from prior experience, and similarity of the sound to biologically important signals (e.g., predator signals).

The importance of spatial relations between noise source and animals was clearly illustrated during an experiment in which southward-migrating gray whales (*Eschrichtius robustus*) were exposed to low-frequency sonar signals projected from a stationary vessel (Clark et al. 1999; Buck & Tyack 2000). Initially the sound source vessel was located in the middle of the whales' migratory path (approximately 2 km offshore). Whales did not avoid the vessel during the control condition (no sound projected; Fig. 1a), but whales avoided the vessel during playback of the sonar sound signals (Fig. 1b). The vessel was then moved approximately 2 km farther offshore, away from the center of the migratory path (Figs. 1c & 1d). During these latter trials, the sound levels received by whales in the migratory path were similar to those in the earlier trials, but whales did not avoid the vessel when the sound was emitted. These results suggest that some factor other than received sound level (e.g., orientation relative to the sound source) has a stronger effect on behavioral response than the sound level. Given these results during migration, the metrics required to assess the response of gray whales to a sound source must include proximity, bearing rate, encroachment (i.e., decreasing or increasing distance between animal and sound source), and animal orientation (e.g., relative orientation score [Bowles et al. 1994]).

Features of the acoustic stimulus itself as it relates to previous experiences of the exposed animal can also affect response. For example, when the sounds of local, resident (i.e., fish-eating ecotype) killer whales (*Orcinus orca*) were played to harbor seals (*Phoca vitulina*), the seals did not respond strongly (Deecke et al. 2002). However, a large number of seals responded strongly to the sounds of transient (i.e., mammal-eating ecotype) killer whales. The interpretation of these observations was that the seals learn to associate the calls with the level of threat from the local resident or transient killer whales. When presented with calls of unfamiliar resident killer whales, the seals' reactions were similar to their reactions to calls of the transient killer whales. There was no opportunity for the seals to associate these unfamiliar calls with a threat, but in the absence of experience, the seals reacted to these novel sounds as if they were from transient, mammal-eating killer whales. These findings are consistent with the hypothesis that biologically important sounds, such as those from a predator, can elicit responses at very low received sound levels, as was observed for migrating gray whales exposed to calls of transient killer whales (Malme et al. 1983). Thus, an animal's prior experience with an anthropogenic sound source can influence the extent to which the animal responds to the sound, independent of the received sound level to which the animal was exposed.

Exposure Metrics

The preceding examples illustrate the potential information that can be gained by expanding the stimulus descriptor beyond the absolute level of received sound. The sonar equation (Urick 1983) is a simple and useful way to relate absolute and relative sound levels, and it illustrates key features of the exposure problem. The

Table 1. Severity index for assessing observed behavioral responses of free-ranging marine mammals and laboratory subjects to various types of anthropogenic sound.[*]

Response score	*Behavior (free-ranging subjects)*	*Behavior (laboratory subjects)*
0	no observable response	no observable response
1	brief orientation response (investigation or visual orientation)	no observable response
2	moderate or multiple orienting behaviors brief or minor cessation or modification of vocalization brief or minor change in respiration rates	no observable negative response; may move toward sound source as a novel object
3	prolonged orientation behavior individual alert behavior minor changes in locomotion speed, direction, or diving profile, but no avoidance of sound source moderate change in respiration rate minor cessation or modification of vocalizations (if duration of sound < duration of source operation)	minor changes in response to trained behaviors
4	moderate changes in locomotion speed, direction, or diving profile, but no avoidance of sound source brief, minor shift in distribution of a group of subjects moderate cessation or modification of vocalization (duration ≈ duration of source operation)	moderate changes in response to trained behaviors (e.g., reluctance to return to station, long intertrial intervals)
5	extensive or prolonged changes in locomotion speed, direction, or diving profile, but no avoidance of sound source moderate shift in group distribution (see above) change in distance among animals or group size (aggregation or separation) prolonged cessation or modification of vocalization (duration > duration of source operation)	severe and sustained changes in trained behavior (e.g., breaking away from station during experimental sessions)
6	minor or moderate individual or group avoidance of sound source brief or minor separation of females and dependent offspring aggressive behavior related to noise exposure (e.g., tail or flipper slapping, fluke display, jaw clapping or gnashing teeth, abrupt directed movement, bubble clouds) extended cessation or modification of vocalization visible startle response brief cessation of reproductive behavior	refusal to initiate trained tasks
7	extensive or prolonged aggressive behavior moderate separation of females and dependent offspring clear antipredator response severe or sustained avoidance of sound source moderate cessation of reproductive behavior	avoidance of experimental situation or retreat to refuge (duration ≤ duration of experiment) threatening or attacking the sound source
8	obvious aversion or progressive sensitization prolonged or significant separation of females and dependent offspring in response to disruption of acoustic reunion mechanisms long-term avoidance of area (duration > duration source operation) prolonged cessation of reproductive behavior	avoidance of or sensitization to experimental situation or retreat to refuge (duration > duration of experiment)
9	outright panic, flight, stampede, attack of conspecifics, or stranding events avoidance behavior related to predator detection	total avoidance of sound exposure area and refusal to perform trained behaviors for longer than a day

[*] *Table modified from Table 4 in Southall et al. (2007).*

absolute-value terms in the sonar equation are in decibels referenced to a standard value of 1 microPascal (1 μPa). The absolute measurement of the received sound pressure level term (RL) is typically annotated to indicate the signal-processing technique used to measure the amplitude. Common processing techniques include root-mean-square (RMS) measurement, the highest or peak value in the signal (PK), and, when duration of the signal is important, the integrated value of the squared signal over time (i.e., sound energy level [SEL]). In this latter instance, the reference value is 1 $\mu\text{Pa}^2 \cdot \text{sec}$ (appendix A in Southall et al. [2007]).

$$\text{RL} = \text{SL} - \text{TL}, \tag{1}$$

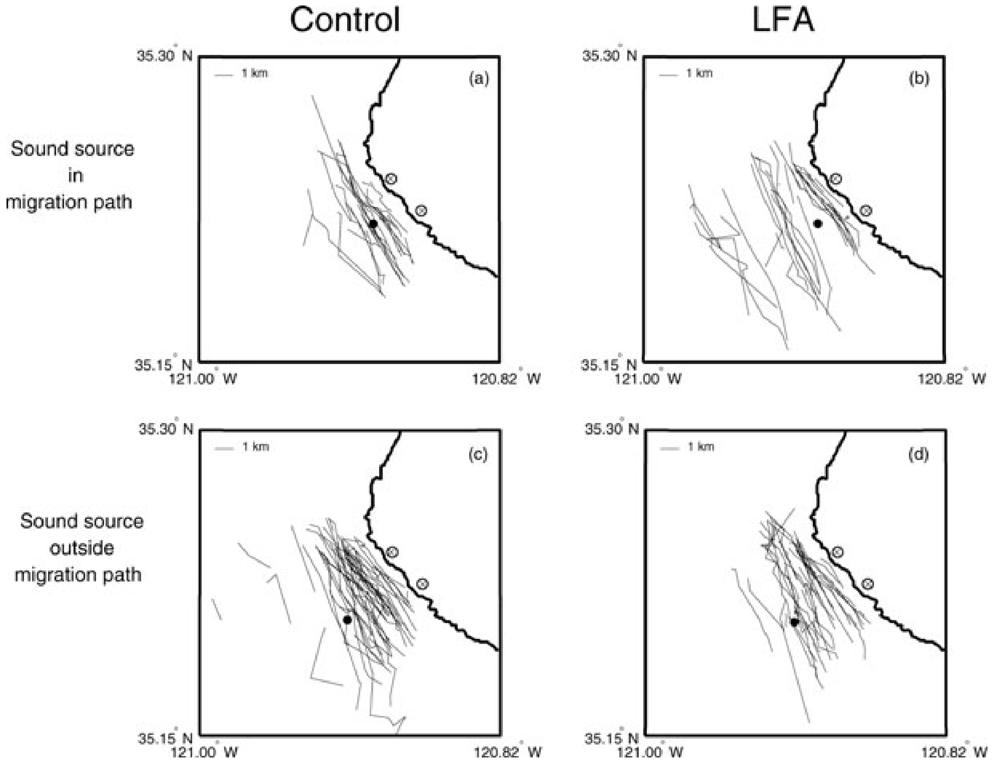

*Figure 1. Examples of behavioral responses of gray whales (*Escrichtius robustus*) to low-frequency active (LFA) sonar signals in different spatial contexts. Pictured are the southbound migration paths of whales off Pt. Bouchon, California (U.S.A.): (a, c) control conditions and (b, d) when LFA sonar signals were projected into the water from a vessel. Circles with an × are onshore tracking stations. In (a) and (b) the vessel (black circle) is approximately 2 km offshore and in (c) and (d) the vessel is approximately 4 km offshore. When the source was moved offshore from the center (2 km) to the edge (4 km) of the migratory corridor, the whales' overt avoidance response disappeared, even though received sound levels were similar.*

where RL is the absolute received level of sound at a given time and location in decibels relative to the standard reference pressure of 1 μPa; SL is the source level of sound transmitted from a source as measured at an effective distance of 1 m; and TL is transmission loss (i.e., the loss in sound level as the sound propagates outward from the source). For a point source in an infinite medium, this value is approximated by $\mathrm{TL} = 20 \log_{10}[R]$, where R is the distance from the source in meters.

An additional indication that a behavioral response may reflect context is a response when an animal first detects a sound. In such a case, the animal could be responding not only to the absolute received level of the sound (RL), but also to the sound level in relation to competing background noise (NL). This relation is defined as the signal-to-noise ratio [SNR]), where

$$\mathrm{SNR} = \mathrm{RL} - \mathrm{NL}, \tag{2}$$

where the measurements of both RL and NL are in the same frequency band, and the noise level is measured in the absence of the signal. In practice, the signal is not always detected at values of $\mathrm{SNR} > 0$, but at some higher level of signal excess (SE) (Clark et al. 2009; Eq. 4):

$$\mathrm{SE} = \mathrm{SNR} - \mathrm{DT}, \tag{3}$$

where DT is the detection threshold, and detection requires that $\mathrm{SE} \geq 0$. By convention DT is the level above background noise at which the probability of signal detection is 50% (i.e., when $\mathrm{DT} = \mathrm{SNR}$ and $\mathrm{SE} = 0$). Noise level is generally the greater of noise or reverberation, if present. Reverberation in this context refers to the backscattering of sound from nearby reflecting boundaries, including volume, bottom, and surface (Urick 1983).

The sonar equation metrics can also be augmented with terms that account for the absolute hearing threshold (TH) of an animal as a function of frequency and amplitude. The relative term, sensation level (SnL), represents the difference between this threshold value and the received level of sound (RL),

$$\mathrm{SnL} = \mathrm{RL} - \mathrm{TH}. \tag{4}$$

Thus, two criteria must be met for a sound to be detected, $\mathrm{SE} > 0$ and $\mathrm{SnL} > 0$.

Reporting the sound-exposure metric in terms of both an absolute level and a relative level is a necessary and important means of identifying both physical and behavioral responses to exposure to anthropogenic sound. The absolute level of sound is the standard metric for assessing the physical effects of acute and chronic exposure, such as temporary or permanent hearing effects. For chronic exposure, metrics that include the integration of exposure to sound over standard periods, such as equivalent-continuous sound level (L_{eq}) and other human-community noise-control metrics, are designed to protect against long-term hearing damage. Community-annoyance standards could also serve as useful templates for the management of acute and chronic exposure to sound in the ocean (Kryter 1994; Harris 1998; Fristrup 2009).

Fully evaluating the ability of animals to detect a sound in a given ambient environment requires knowledge of the absolute level of a sound, the absolute level of background noise, and animal hearing thresholds. We think measures of both background noise and associated factors (e.g., weather, nearby shipping lanes) should be standard measures in the study of behavioral responses to sound.

To date most evaluations and predictions of responses to underwater sound exposure have been based on only the RL value from Eq. 1, where the RMS version of RL is specified by current assessment methods (Southall et al. 2007). However, the RMS metric is inappropriate and inaccurate for most impulsive sources of sound such as seismic airguns (Madsen 2005). Furthermore, the RMS metric is inadequate for assessing a range of hearing effects, including most of the physical effects such as TTS and PTS, which are governed largely by transient characteristics of sounds (e.g., rise time, peak pressure, and signal duration) and chronic exposure. In these cases SEL and PK decibels (Madsen 2005; Southall et al. 2007) are more appropriate and accurate measures.

When contextual variables such as spatial and temporal orientation, current behavioral state, and past experience are recognized as potential factors in the prediction of behavioral response to sound, assessing the relative sound-level metrics (i.e., SE and SnL) becomes more important. We also expect that, as in humans (Yost 2006), known and presumably biologically meaningful sounds, such as those from conspecifics or predators, may be detectable at lower levels than unknown sounds (i.e., detection threshold is lower). Indeed, migrating gray whales avoid signals of killer whales received with an estimated 0 dB SNR (Malme et al. 1983). Furthermore, we think that attention must be given to the natural variability of the acoustic environment in terms of both sound transmission characteristics (TL) and spatial and temporal variations in the background noise level (NL).

The bifurcation of metrics between absolute and relative, as suggested here, still allows for the application of a dose–response (DR) algorithm under certain sound-exposure conditions (i.e., the magnitude of the exposure effect, whether physical or behavioral, increases as the absolute level of the sound exposure increases). Examples of this include physical effects on the hearing mechanism (e.g., increase in TTS up to and including PTS), auditory masking, and perhaps some forms of behavioral annoyance as occur for humans who are exposed to relatively high noise levels (e.g., Harris 1998).

There is no simple boundary between an absolute RL dose–response approach and one dominated by context except perhaps at the extreme high and low limits of RL. In most instances, the behavioral response will be best explained by a weighted combination of absolute RL metrics and contextual metrics (Fig. 2).

When applying the severity index (Table 1), it is compelling to consider associating lower severity scores with largely contextual responses, especially when sounds that are barely detectable above background noise elicit responses. Accordingly, the severity index for the behavioral context could be separated into two classes, one in which lower-level responses (0–4) are more likely described and assessed according to exposure and context, and another in which higher-level responses (5–9) are described and assessed according to dose response. We suggest that midlevel responses (4–5) can best be described with a combination of the two approaches. These classes will likely be robust for anthropogenic signals. However, there are cases (e.g., predator sounds) in which very low received sound levels can elicit higher-level responses, indicating that biological context cannot be dismissed as a variable in predicting or explaining responses, especially to biologically important signals.

Experimental and observational research on the effects of sound on hearing and behavior in marine animals has provided insights into describing responses and assessing these phenomena and their potential applications to management. There are dualities in measures of behavioral responses (e.g., acute responses versus chronic responses; absolute sound levels versus relative sound levels; attraction versus aversion; naiveté versus adaptation; and whether or not a response is biologically significant) that invalidate the use of an absolute, dose–response RL approach.

Acoustic habitats of different groups of marine mammals have profound spatial, spectral, and temporal differences. It is logical to segregate these differences on the basis of function (as has been done in terms of hearing [Southall et al. 2007]). For example, the distinction between the mysticete and odontocete cetaceans is relatively clear. In general, mysticetes can communicate over great distances (100s of kilometers) for long periods (days) in the low-frequency ($<$1 kHz) range. In contrast, odontocetes produce and perceive sounds over middle to short distances (10s of kilometers), over intermediate

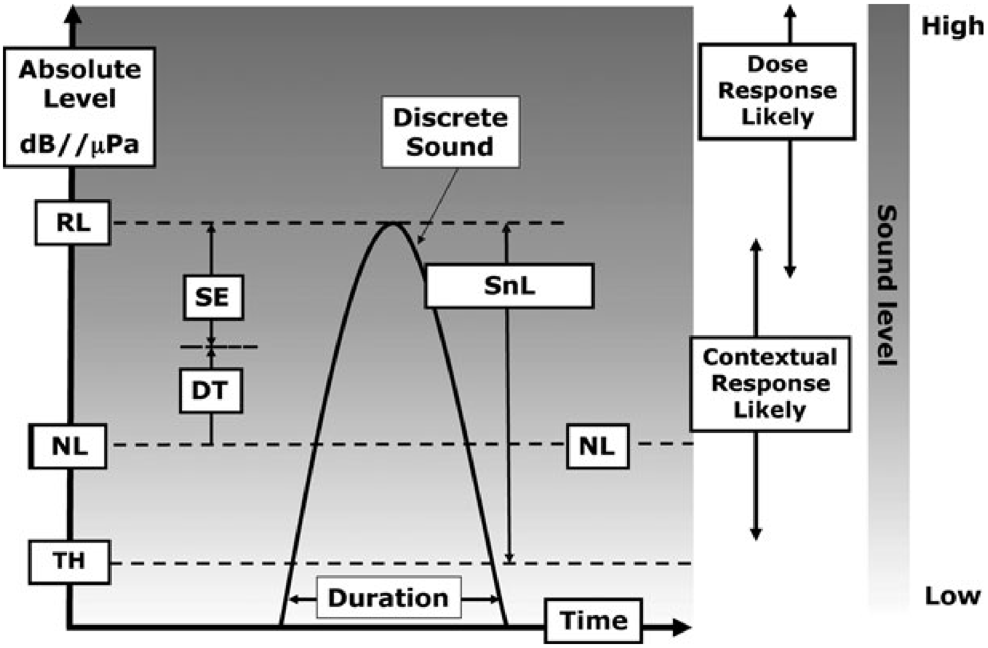

Figure 2. Conceptual illustration of likelihood of a dose–response or contextual response by marine mammals to an anthropogenic sound relative to the absolute sound exposure level, background noise level (NL), and sensation level (SnL). The variable on the y-axis is absolute received sound level of the anthropogenic sound, and NL is constant. As the discrete sound level increases over time, it eventually exceeds the detection threshold (DT), the level above NL at which a listener has a 50% chance of detecting the discrete sound. The discrete sound level continues to rise until it reaches its maximum received level (RL). The difference between the RL and the DT is known as signal excess (SE). For an animal to hear the sound, the RL must also exceed the hearing threshold (TH) (i.e., sensation level [SnL] > 0).

to short periods (minutes) in the mid- (1 kHz $< f <$ 10 kHz) and high-frequency ($f >$ 10 kHz) ranges. Among the reasons for the differences in the perceived acoustic habitats of mysticete and odontocete cetaceans are the physical principles that control the sound fields in these different frequency ranges as well as the variation in animal-hearing sensitivity as a function of frequency. Thus, the potential for physical effects from sound exposure (e.g., TTS) are greater in the frequency range of best hearing (Finneran & Schlundt 2010). As a result of frequency-dependent absorption, transmission loss (TL) for high-frequency sounds (produced by odontocetes) increases rapidly as distance from the source increases (especially above 20 kHz; Urick 1983), whereas for low-frequency sounds (typically produced by mysticetes), absorption plays virtually no role even at distances in excess of 100s of kilometers. Thus, when considering the exposure of odontocetes to high-frequency sound sources, the potential for either injury or behavioral response is likely to be constrained to short distances and to brief exposure periods, whereas for mysticetes the effects of low-frequency sources are likely chronic and occur over greater distances for longer periods.

Given the above considerations, multiple variables likely affect behavioral response to sound. It is recognized that quantification of multiple variables has not been broadly applied to the assessment of behavioral responses to sound, but there is some evidence that regulatory agencies are moving in this direction (Johnson 2012).

Discussion

The focus of previous research on only the acute effects of sound has limited the ability of regulators to effectively manage the potential effects of anthropogenic sounds on marine animal populations. Effective management requires assessment of chronic effects, such as effects on hearing over the long term and the effect of masking on communication. Such chronic effects have long been the principal focus of studies on the effects of terrestrial noise on both humans and other animals (Leu et al. 2008; Hatch & Fristrup 2009). Even minor, acute, contextual exposures to sound, if experienced over a long time, may contribute to a net chronic effect that is undetectable with an acute-centric, dose–response assessment. Communication masking and the long-term proximity and encroachment of sound sources that are associated with increasing levels of human activity are examples of such chronic effects (e.g., Bejder et al. 2006; Clark et al. 2009).

The fact that a wide range of contextual variables associated with exposure to anthropogenic sounds may affect behavioral responses to these sounds is not new (e.g., André et al. 1997; Frankel & Clark 1998; Nowacek et al. 2007). The conceptual approach to the assessment of sound effects we outlined here does not prescribe a complete departure from a dose–response approach because there are conditions, especially those related to high levels of annoyance, auditory masking, and physical effect on hearing, in which RL-based, dose–response relations are likely to exist. However, the existing noise-management approach, which effectively ignores context and relies entirely on assumptions of a RL-based response, is inconsistent with current understanding, is potentially misleading, and in some cases is inaccurate. We think attention to reporting synoptic, multivariate exposure conditions (including those described above) is imperative for ongoing and future research in this field and will significantly reduce the uncertainty in assessment, management, and mitigation of the behavioral effects of exposure to anthropogenic noise.

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