Contributed Paper

Modeling Effectiveness of Gradual Increases in Source Level to Mitigate Effects of Sonar on Marine Mammals

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Abstract: *Ramp-up or soft-start procedures (i.e., gradual increase in the source level) are used to mitigate the effect of sonar sound on marine mammals, although no one to date has tested whether ramp-up procedures are effective at reducing the effect of sound on marine mammals. We investigated the effectiveness of ramp-up procedures in reducing the area within which changes in hearing thresholds can occur. We modeled the level of sound killer whales* (Orcinus orca) *were exposed to from a generic sonar operation preceded by different ramp-up schemes. In our model, ramp-up procedures reduced the risk of killer whales receiving sounds of sufficient intensity to affect their hearing. The effectiveness of the ramp-up procedure depended strongly on the assumed response threshold and differed with ramp-up duration, although extending the duration of the ramp up beyond 5 min did not add much to its predicted mitigating effect. The main factors that limited effectiveness of ramp up in a typical antisubmarine warfare scenario were high source level, rapid moving sonar source, and long silences between consecutive sonar transmissions. Our exposure modeling approach can be used to evaluate and optimize mitigation procedures.*

Keywords: acoustics, killer whales, marine mammals, *Ramp-up procedures*, soft-start procedures, sound impact

Modelado de la Efectividad de los Incrementos Graduales en el Nivel de la Fuente para Mitigar Efectos de Sonar sobre Mamíferos Marinos

Resumen: *Los procedimientos de incremento gradual o de arranque suave (es decir, incremento gradual en el nivel de la fuente) se utilizan para mitigar el efecto del sonido de sonar sobre mamíferos marinos, aunque hasta la fecha nadie ha probado si los procedimientos de incremento gradual reducen con efectividad el efecto del sonido sobre mamíferos marinos. Investigamos la efectividad del incremento gradual en reducir la superficie dentro de la cual se podrían producir cambios en el umbral auditivo. Modelamos el nivel sonoro al que estuvieron expuestas ballenas asesinas* (Orcinus orca) *por la operación de un sonar genérico precedida por diferentes esquemas de incremento gradual. En nuestro modelo, los procedimientos de incremento gradual redujeron el riesgo de que las ballenas asesinas recibiesen sonidos de intensidad suficiente para que afectase su audición. La efectividad del procedimiento de incremento gradual dependió estrechamente del umbral de respuesta supuesto y varió según la duración del procedimiento, aunque aumentar esta duración hasta más de 5 minutos no añadió mucho al efecto mitigante pronosticado. Los factores principales que limitaron la efectividad del incremento gradual, en un escenario de guerra antisubmarina, fueron el nivel de la fuente, el movimiento rápido de la fuente y los silencios prolongados entre transmisiones consecutivas del sonar. Nuestro método de modelado de la exposición puede ser utilizado para evaluar y optimizar procedimientos de mitigación.*

Introduction

Regulations aimed at reducing the effect of underwater sound on marine mammals have been put in place worldwide (EC 2008; Daly & Harrison 2012). For anthropogenic activities involving loud sources of sound, regulators often require actions to reduce the effects. Sometimes ramp-up (or soft-start) procedures are adopted in which the level of sound of the operation is gradually increased at the start of an operation. The idea is that the gradual increase in source level offers animals near the source the opportunity to swim away and thus potentially decreases effects once the source reaches full power. Ramp-up schemes are used for seismic surveys (Weir & Dolman 2007; Compton et al. 2008) and other offshore activities such as pile driving (David 2006). Several navies have adopted ramp-up procedures in an attempt to mitigate effects on marine mammals of sonar used in antisubmarine warfare (Dolman et al. 2009).

There is growing evidence that intense sound sources can have adverse effects on marine mammals, which have sensitive hearing and rely on sound to communicate, orientate, and forage underwater. Studies on the effect of sounds on hearing indicate that intense sound can temporarily impair hearing (called a temporary threshold shift [TTS]) and, theoretically, can lead to lasting physical damage of the mammalian auditory system (i.e., permanent threshold shift [PTS]) (Southall et al. 2007). It is generally believed that impaired hearing may reduce the capability of marine mammals to navigate, forage, interact socially, and detect predators (NRC 2005).

A ramp-up scheme is generally implemented as a common-sense precautionary procedure (e.g., JNCC 2004; IWC 2006). To actually mitigate the risk of severe hearing effects, the sonar has to trigger an avoidance response in the animal to allow enough time for it to move far enough away to significantly reduce the risk of adverse effects of exposure to the more intense full-power source. Clear avoidance responses to sonar signals are reported for different marine mammal species. For instance, controlled sonar exposure experiments led to repeated avoidance of killer whales (*Orcinus orca*) to an approaching ship that was transmitting sonar sounds in the 1–2 kHz or 6–7 kHz ranges (Miller et al. 2012). Other species, such as beaked whales (Ziphiidae), were observed to respond strongly to sonar playbacks by evacuating the area of sonar operation (Tyack et al. 2011). Because no theoretical or experimental studies have been conducted that demonstrate ramp up is beneficial, the effectiveness of ramp-up procedures for risk mitigation is still under debate (Stone & Tasker 2006; Weir & Dolman 2007; Dolman et al. 2009). In principle a ramp up might

do more harm than good if animals are attracted to the ramp up or if it increases the amount of time animals are exposed to the sound. In addition, complex sound propagation paths can sometimes result in an increase in received sound levels with increasing distances from the source, which would counteract the benefit of increased separation between the animal and the source.

To investigate the effectiveness of ramp-up during a sonar operation, we built an exposure model to compare modeled effects of operations with ramp up with operations without ramp up. Recent observations of marine mammals responding to sonar sound (Miller et al. 2012) provide a basis for modeling the response of marine mammals and allow a first assessment of the efficacy of ramp up in reducing the effect of sonar operations. We investigated the effect of various ramp-up design parameters (total ramp-up duration, pulse-repetition time) and model parameters (exposure level at which animals avoid a sound source, ship speed, and animal swim speed) on the computed area affected by a sonar.

Methods

Model Overview and Simulated Sonar Operations

We calculated the cumulative sound exposure of a sonar operation by simulating movement of a sonar source through an area populated by marine mammals and modeling the movement responses of the animals to the sonar. To assess the benefit of a ramp up, we computed the area over which a hearing effect was predicted for various scenarios. Each scenario involves the outcome of use of a ramp-up procedure with specific design parameters and avoidance-movement response models. We compared outcome of this set of ramp-up scenarios with identical scenarios in which no ramp-up preceded the sonar operation (referred to as the no ramp-up scenarios).

We considered a single sonar platform moving at a constant velocity. The operation had 2 phases: ramp-up phase, in which the sonar transmits pulses with gradually escalating source levels specifically designed to mitigate sonar effects, and operational phase, in which the sonar transmits an operationally relevant transmission scheme to detect targets at long distances.

We assumed an omnidirectional sonar source transmitting a 3 s duration signal in the frequency range of 1–8 kHz (a typical frequency range for military search sonars [Ainslie 2010]) moves in a straight line. A source level of 225 dB re 1 μPa^2 m^2 was adopted during the operational phase; this level is in the range of published values of operational source levels of tactical naval sonars
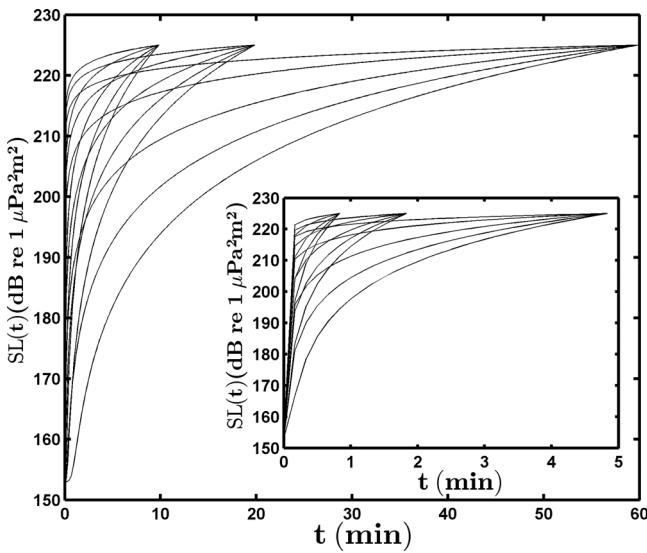
Figure 1. Change in sonar source level (SL) over time (t) for ramp-up schemes tested in this study. The inset shows the ramp-up durations of <5 min. In addition to the duration of the ramp-up (T_{ramp}) and the ramp-up exponent (n_{ramp}), the pulse-repetition time (PRT) varied. Values for different ramp-up design parameters are provided in Table 1.

(210–240 dB re 1 $\mu Pa^2 m^2$ [Ainslie 2010]). The sonar source transmits with a constant source level and fixed pulse-repetition time (PRT) of 30 s during the entire operational phase. We considered scenarios with ship speeds of $v_s = 6$, 4, and 2 m/s (approximately 12, 8, and 4 knots) that were fixed throughout the ramp-up and operational phases.

Parameterization of the Ramp-up Procedure

We used the following function to parameterize the change in source level (SL) with time (t) during the ramp up:

$$\mathrm{SL}_{\mathrm{ramp}}(t) = \mathrm{SL}_{\min} + (\mathrm{SL}_{\max} - \mathrm{SL}_{\min}) \left(\frac{t}{T_{\mathrm{ramp}}} \right)^{-n_{\mathrm{ramp}}} \text{ for } t < T_{\mathrm{ramp}},$$

(1)

where $\mathrm{SL}_{\min}$ and $\mathrm{SL}_{\max}$ are the start and end sound level, T_{ramp} is the ramp-up duration, and n_{ramp} is the ramp-up exponent, which represents the escalation rate of the sound source We varied 3 design parameters for the ramp-up scenarios: T_{ramp}, n_{ramp}, and PRT. The ramp up scenarios we considered are depicted in Figure 1.

Practical considerations provide a lower limit and an upper limit to the ramp-up duration; the lower limit is determined by the time needed for an animal to substantially increase the distance to the source. In principle, the maximum ramp up is unlimited; however, in practice it will be determined by operational limitations. We varied T_{ramp} from 60 s to 1 hour.

Naval sonars can have a limited dynamic range in source level. We used a large dynamic range in source level of 60 dB, and the maximum source level $\mathrm{SL}_{\max}$ was equal to the source level of the operational phase. We adopted a fixed-pulse repetition time for each ramp up. For different ramp-up scenarios, the PRT varied between 5 and 20 seconds.

Pulse length (T_{pulse}) affects the total energy transmitted by the source. We chose a short pulse length to reduce the cumulative exposure as much as possible, but we ensured it would be long enough so that the loudness of the sound would not increase if the pulse were longer. The effect of pulse length on loudness perception (loudness summation) has not been studied in marine mammals, but its effect on hearing thresholds has been measured in other odontocete species and with hearing integration times that correspond to 200–600 ms for frequencies between 1 and 8 kHz (Kastelein et al. 2010). We therefore adopted a pulse length of 500 ms during the ramp-up phase, which falls in the range of typical pulse lengths used by sonar systems.

Sound Propagation Model and Computational Grid

We used a simple acoustic propagation model to reduce the computational complexity and as a simplification to uncover the basic mechanisms that determine effect of ramp-up schemes on the effect of a sonar operation in general. For propagation losses, spherical spreading was adopted and absorption was negligible. We also ignored depth dependence of sound propagation. Exposure computations were performed for a set of simulated animals encountered during the operation. For each simulated animal, we computed cumulative sound exposure level (SEL) and the maximum received sound pressure level ($\mathrm{SPL}_{\max}$) over all transmissions. For definitions of SPL and SEL we followed Ainslie (2010). Simulated animals were distributed uniformly over a 2-dimensional grid around the sonar track at the start of the operation. Because of the large dynamic scale in exposure levels that relate to hearing effects and disturbance effects (and thus distances over which these are effected), the computational grid consisted of increasing resolution from 500×500 m^2 at large distances (> 10 km) to 1×1 m^2 close (<2 km) to the source track. This achieved sufficient resolution for the model while reducing the computational time. The exposure model resulted in a prediction of the $\mathrm{SEL}(x,y)$ and maximum $\mathrm{SPL}_{\max}(x,y)$ that the simulated animal receives due to the entire operation for each starting at position (x,y).

Simulated Animal Movement Behavior

The simulated animal-avoidance behavior was based on the observation that killer whales repeatedly moved almost perpendicular to the heading of the oncoming

source in response to controlled exposures of naval sonar (Miller et al. 2012). Avoidance speeds observed for killer whales vary between 1 and 4 m/s in response to approaching sonar (Miller et al. 2012). On the basis of these observations, we adopted an avoidance response in the direction perpendicular to the ship track in each scenario. We considered constant-avoidance swim speeds of 0.5, 1, and 4 m/s. We assumed simulated animals continued to respond throughout the remainder of an operation.

The onset of avoidance responses is usually associated with the received SPL of the disturbance stimulus at the location of the simulated animals (Southall et al. 2007). Simulated animals were assumed to initiate an avoidance response once they receive an SPL exceeding a predefined avoidance threshold (SPL_{avoid}). Marine mammals tend to respond behaviorally at a wide range of received levels of sound pressure (Southall et al. 2007; Miller et al 2012). These behavioral differences can be due to individual variation, but they also reflect that other factors, such as behavioral context, determine responsiveness (Ellison et al. 2012; Miller et al. 2012). A single step-wise avoidance threshold is inappropriate to capture the variation in responsiveness observed for killer whales.

We accounted for the effect of variability in responsiveness on the effectiveness of ramp up by characterizing the variability in responsiveness with a family of dose-response functions. We chose these functions so as to cover the range of SPL values (82–180 dB re 1 μPa^2) measured by Miller et al. (2012) in controlled exposure experiments with acoustically tagged cetaceans.

We defined a dose-response relation, P_{avoid} ($<SPL_{avoid}$), as the proportion of animals in a population that have initiated an avoidance response at any SPL $< SPL_{avoid}$. We adopted a generic dose-response relation with the functional form of

$$P_{avoid}(< SPL_{avoid}) = \frac{1}{1 + e^{-(a_{dr} + b_{dr}SPL_{avoid})}}, \quad (2)$$

where a_{dr} and $b_{df} = -a_{dr}/SPL_{50\%}$ and determine the slope of the dose-response curve and $SPL_{50\%}$ is the SPL at which 50% of the population has initiated an avoidance response to the sonar.

Effect Indicators and Affected Area

Two commonly accepted risk indicators were adopted: physical hearing injury (delimited by the onset of PTS) and TTS, both are assumed to arise from the SEL_{risk} received by the animals (Southall et al. 2007). Thresholds for PTS and TTS onset have not been measured directly for killer whales. Southall et al. (2007) group the killer whale into the "mid-frequency cetaceans" functional hearing group in their proposed acoustic criteria for the onset of TTS and PTS. Adopting a weighting for the midfrequency cetacean functional hearing group, which

is flat in the frequency range between 1 kHz and 10 kHz, the weighted TTS and PTS thresholds correspond to the SEL values of 195 dB re 1 μPa^2s and 215 dB re 1 μPa^2s, respectively. We used these values in our study.

We expressed the risk of sonar operation in terms of an affected area, which we defined as the area over which simulated animals are exposed to an SEL exceeding some threshold that relates to either PTS or TTS. We calculated affected area (A) by summing over all starting positions (x,y) where the risk threshold SEL_{risk} was exceeded for a fixed avoidance threshold SPL_{avoid}:

$$A_{SELrisk}(> SEL_{risk}) = \int_x \int_y H(SEL(x,y) - SEL_{risk})dx\,dy,$$

$$(3)$$

where H(SEL) is the Heaviside step function.

For each model run, the computed affected area for a given avoidance threshold SPL_{avoid} was weighted by the probability, $p(SPL_{avoid})$, that animals respond at this avoidance threshold (derivative of Eq. 2). These weighted areas of effect were summed resulting in a mean affected area ($\overline{A}$):

$$\overline{A}(> SEL_{risk}) = \frac{\int p(SPL_{avoid})A(> SEL_{risk}, SPL_{avoid})dSPL_{avoid}}{\int p(SPL_{avoid})dSPL_{avoid}}.$$

$$(4)$$

All model parameters are summarized in Table 1.

To understand the interaction of a ramp-up design and the simulated animal behavior on the computed effect of sonar sound, we started by considering a fixed avoidance threshold SPL_{avoid}. We explored the effect of varying SPL_{avoid} level on affected area. We then investigated the effect of variability in responsiveness by weighting affected area with different dose-response relations for avoidance response. The sensitivity of the computed affected areas to these parameters was assessed by varying the ship speed and avoidance speed.

Results

Effect of Avoidance Threshold on Affected Area

We considered the effect of ramp up on affected area, assuming that all simulated animals started responding to the sound at a fixed SPL_{avoid} (Fig. 2). The effectiveness of ramp up depended on the responsiveness of the simulated animal (Fig. 2). For responsive animals (low SPL_{avoid}), many ramp-up designs significantly lowered the affected area, A (SEL $> SEL_{risk}$), (Eq. 3) relative to the no ramp-up scenario (Fig. 2). A large variation in the reduction of affected area indicated that some ramp-up designs were more effective than others (Fig. 2).

A sharp transition in computed affected area occurred between $SPL_{avoid} = 170$ and 180 dB re 1 μPa^2, where the affected area increased by 2 orders of magnitude (Fig. 2). For relatively unresponsive animals (high SPL_{avoid}), the

Table 1. Simulation parameters used to describe the default sonar operation and characterize the ramp-up procedure for the marine mammal behavioral model and sonar sensitivity levels.

Parameter	Value	Description
Sonar operation		
T_{op}	3600 s (1 h)	duration of operational phase
SL_{op}	225 dB re 1 μPa^2 m^2	source level during operational phase
PRT_{op}	30 s	pulse-repetition time during operational phase
T_{pulse}	3 s	pulse duration during operational phase
v_{ship}	6 m/s, 4 m/s, 2 m/s	ship speed during operational phase
Simulated animal		
v_{animal}	0.5 m/s, 1 m/s, 4 m/s	simulated animal avoidance speed
SEL_{TTS}	195 dB re 1μPa^2 s	risk threshold for TTS
SEL_{PTS}	SEL_{TTS} + 20 dB	risk threshold for PTS
$SPL_{50\%}$	125, 145, 165 dB re 1μPa^2 (low to high)	midpoint of dose-response relation for simulated animal avoidance behavior
a_{dr}	45, 35, 25, 15, 5 (shallow to steep)	steepness of dose-response relation for simulated animal avoidance behavior
Fixed ramp up		
SL_{max}	225 dB re 1 μPa^2 m^2	maximum source level during ramp up
SL_{min}	165 dB re 1 μPa^2 m^2	minimum source level during ramp up
T_{pulse}	0.5 s	pulse duration during ramp-up phase varied ramp up
T_{ramp}	0, 60, 300, 600, 1200, 3600 s	ramp-up duration
n_{ramp}	1, 2, 3, 4	ramp-up exponent
PRT	5, 10, 20 s	pulse-repetition time during ramp up

ramp-up procedure increased the affected area relative to the no ramp-up scenario. The sudden transition occurred because the ship's speed was such that by the time the whale heard a ping that triggered avoidance, it did not have time to move a safe distance before subsequent pings sounded. Unresponsive animals were not alarmed by previous transmissions and experienced high exposure levels due to close passage of the sonar source during subsequent transmissions. This transition point occurred roughly under the following condition:

$$v_{ship} \times PRT > (1m) \times 10^{\frac{SL - SPL_{avoid}}{20}}. \qquad (5)$$

The risk of animals not responding to previous transmissions is more likely to occur for fast-moving ships with long silences between transmissions, which is typical for ship-based tactical sonars carrying out long-range search operations. These silences pose a potential risk for marine mammals that respond only at high SPL because the animal may not respond until the sonar is close enough for one transmission to cause TTS or PTS. Each full-power transmission then occurs in an area where animals have not yet responded to the moving sonar and the total affected area becomes the sum of affected areas around each individual transmission. In this situation, a ramp-up may only mitigate the risk of the first full-power transmission, but the remainder of the operational phase remains unaffected by the ramp-up and dominates the total effect of the operation.

Effect of Variability of Avoidance Thresholds on Affected Area

Differences in animal responsiveness (reflected by shape and position of the dose-response curve [Figs. 3 & 4]) was a biological parameter that had a strong effect on mean affected area (A) (Eq. 4) and effectiveness of a ramp-up scheme. Mean affected area ranged from 100 m^2 to 0.5 km^2, depending on the type of dose-response curve adopted.

A general trend could be observed that the mean affected areas increased as the $SPL_{50\%}$ increased and as the steepness of the dose-response curves decreased (Fig. 3).

A second trend was that the efficacy of ramp up, measured as the ratio between the mean affected area due to an operation preceded by a ramp-up compared with the no ramp-up scenario, decreased as $SPL_{50\%}$ increased and as steepness decreased (Fig. 4). For a steep dose-response curve with low $SPL_{50\%}$ the reduction in affected area was at times more than one order of magnitude (Fig. 4). For a shallow curve or high $SPL_{50\%}$, the reduction was <5% for ramp-up durations of a few minutes and increased relative to a no ramp-up scenario with longer ramp-up durations. This was caused by large effect occurring when individuals had a high SPL_{avoid}. The weighting of the affected area by the dose response (Eq. 4) resulted in a large contribution from the effect at high SPL_{avoid} to the mean affected area, even though the fraction of animals in a population responding at those SPL_{avoid} was low (in this case about 10%).
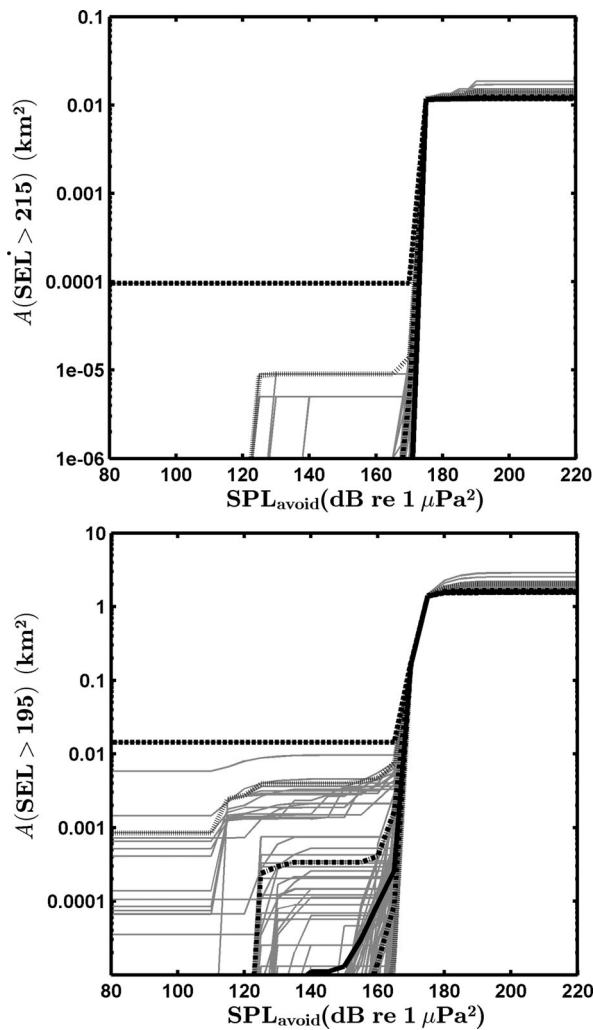
Figure 2. The total area (A) affected by a 1h sonar operation under different ramp-up schemes assuming simulated animals respond at fixed avoidance thresholds (SPL_avoid; sound pressure level at which simulated animal starts to avoid the sonar) from 80 to 220 dB re 1 µPa² in steps of 5 dB: top figure, affected area in which simulated animals were exposed to cumulative sound exposure level (SEL) > 215 dB re 1 µPa²s (the permanent threshold shift [PTS] risk threshold for mid-frequency marine mammals [Southall et al. 2007]); bottom figure, affected area in which simulated animals were exposed to SEL > 195 dB re 1 µPa²s (temporary threshold shift [TTS] risk threshold for mid-frequency cetaceans [Southall et al. 2007]) (gray lines, ramp-up scenarios with different combinations of ramp-up duration, pulse-repetition time [PRT], and ramp-up exponent [as shown in Fig. 1]); solid line, median; dashed and dotted lines, 25th and 75th percentiles respectively; hash-mark lines, 5th and 95th percentiles, respectively (percentiles were computed over all ramp-up scenarios for each avoidance threshold and indicate differences in computed effect due to different ramp-up scenarios); dashed line, effect when no ramp-up is used.

The ramp-up duration appeared to be the dominant ramp-up design parameter for determining its effectiveness. However, at least 80% of the reduction in the mean affected area was already obtained for ramp-up durations of 5 min, which is short compared with the duration of the operational phase (1 h). For ramp-up durations >2 min, the variation in mean affected area in different design parameters (PRT and n_{ramp}) was small compared with the mean trend (Figs. 3 & 4).

Sensitivity of Affected Area to Animal and Ship Speed

Varying the animal avoidance speed primarily affected the absolute affected area and had less effect on the relative efficacy of the ramp up (Fig. 5). Ship speed affected the ramp-up efficacy more strongly. As ship speed decreased mean affected area increased in the no ramp-up scenarios due to the higher contribution of repeated exposures at the start of the operation. However, because modeled animals were more likely to move an effective distance away from the source with lower ship speeds (Eq. 5), affected area decreased for longer ramp-up durations as ship speed decreased.

Discussion

Effectiveness of Ramp Up

We evaluated the effectiveness of ramp up by testing whether affected areas can be reduced (Fig. 3).

The size of the computed mean affected areas and the ability of ramp up to reduce the affected area depended strongly on the responsiveness of the animals. The computed mean affected area increased when animals were less responsive, but at the same time effectiveness of the ramp up decreased. When an unresponsive dose-response relation was adopted, the computed mean affected area with a no ramp-up scenario ranged from 0.1 to 1 km², and the reduction in affected area due to a short ramp-up was small or increased when ramp-up durations were long. This increase in mean affected area for long ramp-up durations was up to a factor of 2, indicating that long ramp-up duration should be avoided in the presence of unresponsive animals. When more animals started avoiding lower received levels of sound, a large relative reduction was achieved with a ramp-up of a few minutes, but the mean affected areas predicted without ramp-up were already low (approximately 100 m²). An estimate of the number of affected animals can be obtained by multiplying the computed affected area by the density of animals (animals per square kilometer) and therefore depends on the abundance of the species in the operation area being considered.

The responsiveness of animals exposed to sound is not a design parameter that can be modified within ramp-up procedures, but it is critical information needed to
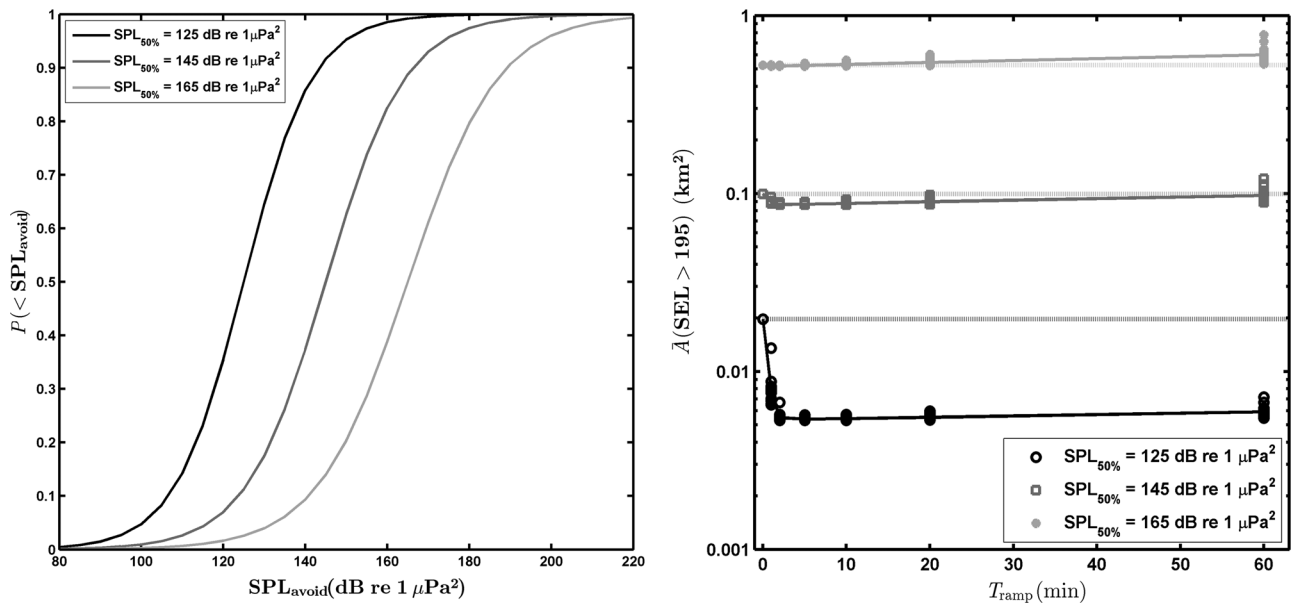
Figure 3. Effect of differences in animal responsiveness to sonar sound on mean affected area ($\overline{A}$) by a 1 h sonar operation preceded by different ramp-up schemes: left panel, dose-response curves (defined by Eq. 2) for different, 50%-avoidance sound pressure levels (SPL$_{50\%}$, upper right box) with steepness of dose response fixed at 35; right panel, corresponding mean area affected ($\overline{A}$) for each ramp-up scenario as a function of ramp-up duration (mean affected area is expressed in terms of sound exposure level [SEL] > 195 dB re 1 μPa^{2}s (temporary threshold shift); solid lines, mean trend through all ramp-up scenarios for each dose-response curve; dotted lines, mean area affected resulting from a no ramp-up scenario from which the relative reduction for different ramp-up durations can be assessed.

evaluate whether ramp-up procedures are effective in the real world. Miller et al. (2012) measure avoidance onset levels for killer whales ranging from 92 to 167 dB re 1 μPa^2. Miller et al. (unpublished) fit a Bayesian dose-response relation to their measurements and found an SPL$_{50\%}$ avoidance threshold of 147 dB re 1 μPa^2 for sonar in the 1–2 kHz frequency range.

Figure 4 shows the Miller et al. (unpublished) dose-response relation superimposed over the generic dose-response relation we considered. The mean curve is shallow and lies somewhere between the a_{dr} = 45 and 35, suggesting the affected area of the sonar operation we considered was 30% lower when the operation was preceded by a ramp up (Fig. 4). This conclusion, however, depends strongly on the shape of the dose-response relation at high SPL$_{avoid}$ values. In the sonar operation scenarios we considered, a transition from low to high affected area occurred when a substantial percentage of the population of simulated animals started moved to avoid SPLs over approximately 170–180 dB re 1 μPa^2 (Fig. 2). This transition was associated with a substantial fraction of the population failing to respond to previous sonar transmissions. The transition point to a larger affected area observed in Figure 2 between avoidance thresholds exceeded measured levels reported for killer whales avoiding sonar sources, which were always considerably <170 dB re 1 μPa^2 (Miller et al. 2012). The effectiveness of the

ramp up for unresponsive animals therefore relies on extrapolating the dose-response relation to higher SPL$_{avoid}$ values than were actually measured. Figure 2 implies a much larger reduction in affected area for the range of SPL measured by Miller et al. (2012) (SPL$_{avoid}$ < 170 dB re 1 μPa^2). The real-world reduction in ramp-up effect on killer whales may therefore be more than suggested in this study.

The duration of the ramp up was the dominant design parameter that determined the effectiveness of ramp up. However, most of the reduction in affected area occurred for ramp-up durations of just a few minutes, much smaller than the total time of the modeled sonar operation (1 h). The extra mitigating benefit of extending the ramp up beyond a few minutes was negligible, except when a high fraction of the animal population had low avoidance thresholds. This result was robust against variations in model parameters. A reduction of ship speed decreased the total affected area and increased the effectiveness of ramp up.

A ramp up is designed to elicit an avoidance response in marine mammals, but such practices can be considered a form of behavioral disturbance. Therefore avoidance responses or weaker behavioral responses to sonar cannot be mitigated for by definition with ramp up. However, more severe forms of disturbance (such as panic) could potentially be mitigated for with ramp up. The relation
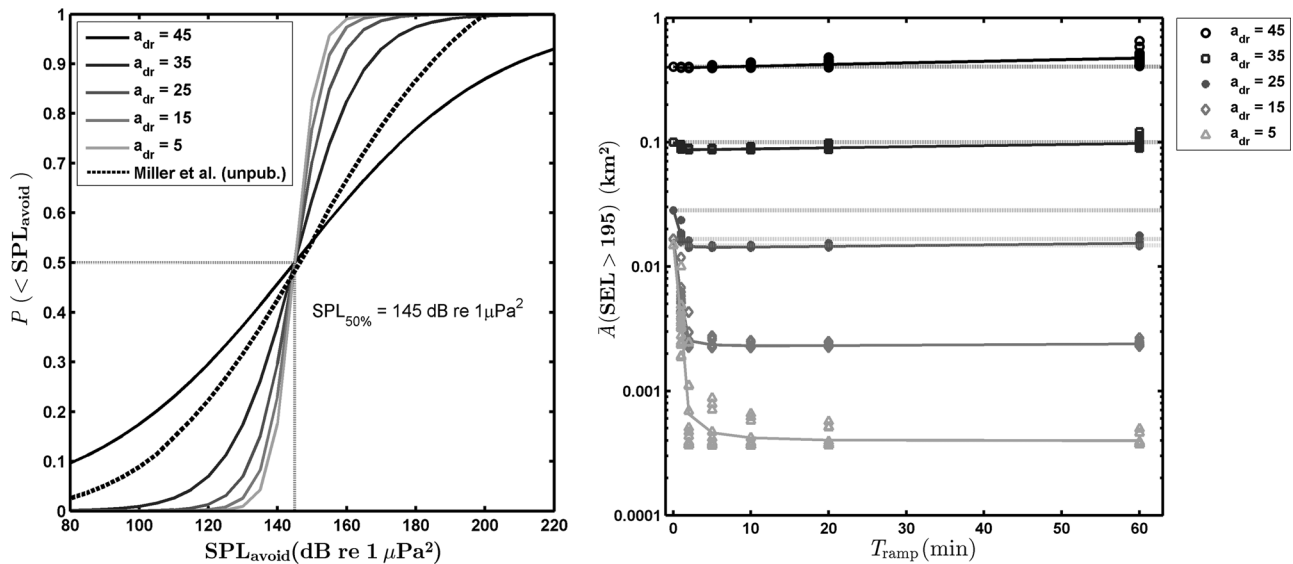
Figure 4. Effect of variation in animal responsiveness to sonar sound on mean area affected ($\overline{A}$) by a 1 h sonar operation preceded by different ramp-up schemes: left panel, dose-response curves (defined by Eq. 2) for fixed 50% avoidance sound pressure levels (SPL$_{50\%}$); SPL$_{50\%}$ is defined as the SPL at which 50% of the population has initiated an avoidance response to the sonar) with different steepness of dose-response (a_{dr}) from 45 (black, solid, shallow line) to 5 (light gray, steepest line) (dashed line, observed dose-response relation for avoidance by killer whales of sonar sound as measured by Miller et al. (unpublished); right panel, corresponding mean area affected ($\overline{A}$) expressed in terms of sound exposure level [SEL] > 195 dB re 1 $\mu Pa^2 s$ (temporary threshold shift) (solid lines, mean trend for all ramp-up scenarios for each dose-response curve; dotted lines, mean affected area resulting from a no ramp-up scenario that can be used to compare the relative reduction for different ramp-up durations.

between sound dosage and disturbance is still a point of debate (Southall et al. 2007; Ellison et al. 2012; Miller et al. 2012). Miller et al. (2012) found there is no clear correlation between dose and severity of the behavioral response. Thus, in cases where the avoidance response triggered by the ramp up happens at higher SPLs than the more severe behavioral disturbance one is trying to mitigate, ramp up will not be effective. In our study, ramp-up schemes reduced affected area when the maximum SPL exceeded 150 dB re 1 μPa^2. However, the potential for behavioral disturbance resulting from lower maximum SPL (< 150 dB re 1 μPa^2) was not significantly affected by the ramp up. At the larger distances corresponding to these lower received levels, the maximum SPL was determined mainly by the full-level sonar transmissions during operational phase. It is hard to draw any firm conclusions from this, but it suggests that ramp-up procedures are not effective at mitigating large-scale behavioral disturbance.

Simulated Animal-Model Assumptions

A key assumption in our model was that the SPL received by the simulated animal determines the onset of an avoidance response. Southall et al. (2007) relate the onset of behavioral responses to received SPL reported in the literature. They adopted SPL mainly because this

was most often reported in the literature; however, other factors may affect the onset of a behavioral reaction, such as distance to the source or the behavioral state of the animal (Southall et al. 2007; Ellison et al. 2012; Miller et al. 2012). Differences in responsiveness due to these other factors are to some extent reflected in the width of the dose-response curves we considered.

We based the simulated avoidance behavior on detailed observations of avoidance responses of killer whales to sonar (Miller et al. 2012). With our modeled avoidance response, we assumed that once simulated animals started avoiding the sound source, they would move perpendicular to the trajectory of the ship for the remainder of the operation. Modeling avoidance as perpendicular to the ship's track is a simplification. Killer whales have been seen turning away from sonar after some time during exposure experiments (Miller et al. 2012). The effect of departures from a perpendicular avoidance track does not strongly affect the outcome of the computed exposure on a killer whale avoiding a sound source, unless animals swim away from the source (Wensveen 2012). Because most of the sound exposure to the simulated animal occurred during the short period when the ship passed by the animal, we expect the effect of continued movement of the animals on the calculated affected area to be minor. However, if ship movement is not rectilinear, as we assumed here, and is instead more random, a brief
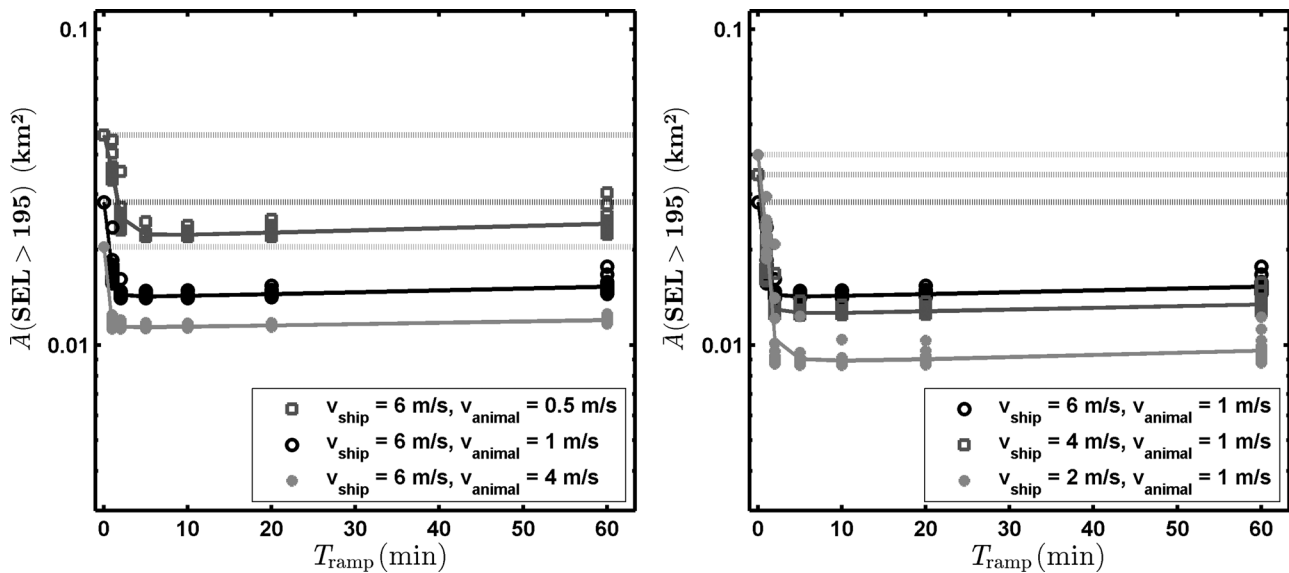
Figure 5. Mean affected area ($\overline{A}$) for different sonar ramp-up durations and different animal-avoidance speeds (left panel) and ship speeds (right panel) (dotted lines, mean affected area resulting from a no ramp-up scenario that can be used to compare the relative reduction for different ramp-up durations). Mean affected area is for animals exposed to sound exposure levels (SEL) > 195 dB re 1 $\mu Pa^2 s$ (corresponding to temporary threshold shift [TTS] for mid-frequency cetaceans [Southall et al. 2007]). We used an intermediate dose-response (Eq. 4) to compute mean affected areas and assumed 50% of the animals avoid the source at sound pressure level < $SPL_{50\%} = 145$ dB re 1 μPa^2 and an intermediate slope (25) of the dose response (see dark gray curve in top panels of Fig. 3).

response may increase the risk of repeated exposure. Other species may have other strategies for avoidance, such as vertical avoidance (Würsig & Richardson 2002; Miller et al. 2012) or movement directly away from the source (Kvadsheim et al. 2011). Movement directed away from the source could only reduce exposure levels if the avoidance speed of the animal were much greater than the approach speed of the source. Otherwise it may cause increased exposure due to a longer proximity of the animals to the source.

The risk thresholds for onset of TTS and PTS in response to sonar sound exposure were based on generic criteria proposed by Southall et al. (2007). Actual TTS measurements have not yet been performed for killer whales. Adopting different risk thresholds will affect the absolute affected areas where TTS and PTS are predicted to occur. However, we found similar trends for affected areas with ramp-up duration for both 195 and 215 dB re 1 $\mu Pa^2 s$, indicating that in general the effectiveness of ramp up at reducing the effect of sonar, relative to full power start-up of the operation, was not strongly affected by the precise choice of the risk thresholds.

Alternative avoidance strategies and onset level of TTS and PTS as function of sound frequency, exposure SPL and duration, individual variation in TTS onset, and growth and recovery functions can be incorporated in exposure modeling (e.g., Houser 2006; Finneran et al. 2010; Gedamke et al. 2011; Schecklman et al. 2011).

Sound-Propagation Model

We used a simple acoustic-propagation model; thus, we assumed spherical spreading and negligible absorption effects. Absorption is negligible on scales at which PTS and TTS occur for the sonar pulses we considered. Realistic propagation conditions are likely to affect the absolute risk calculations of our model but are not likely to affect our key goal, to examine the relative effectiveness between a full-power start of an operation and an operation preceded by a ramp up. More realistic propagation models that can capture realistic propagation conditions can be easily incorporated into this framework to evaluate the risk of specific operational conditions.

Operational Implications

Our results suggest that ramp-up protocols prior to sonar operations can be effective at reducing the number of marine mammals experiencing sound doses that are high enough to cause temporary or permanent threshold shifts. Although a poorly designed ramp up may increase the risk, appropriate ramp-up procedures of only a few minutes duration and relatively short pulses may reduce the risk of animals receiving sound dosages high enough to affect hearing. For a fixed duration of sonar operation, reducing ship speed will further decrease the effect and increase the efficacy of ramp up. The predicted effectiveness of the ramp-up procedure depended strongly

on the assumed responsiveness of marine mammals and was determined primarily by ramp-up duration. In most scenarios, extending the duration of the ramp-up beyond a few minutes did not add much to its mitigating effect, unless a high fraction of a population of animals respond at very low SPL. A key limitation of the effectiveness of ramp up in a typical antisubmarine-warfare scenario is the combination of high source levels and a rapidly moving sonar source in combination with long silences between consecutive full-power sonar transmissions. The risk of these long silences could potentially be mitigated by dedicated mitigation pings between the regular sonar transmissions. The benefit of these extra pings should be carefully balanced against increased amount of noise introduced that potentially may lead to increased disturbance.

The framework of our approach can be applied to other situations for which ramp-up schemes could be used as a mitigation strategy. For example, seismic surveys and offshore industrial activities (e.g., pile driving) also use ramp-up schemes (David 2006; Weir & Dolman 2007). Critical research questions that need addressing to make the work applicable to sound sources other than sonar and species other than killer whales are careful documentation of the avoidance strategies (horizontal avoidance, vertical avoidance, swim speeds), behavioral context, and estimates of sound dosage that predicts onset of avoidance response for other types of sounds. For species that are unresponsive to sonar sound, specific warning signals designed to be more effective in eliciting the desired avoidance response, while still minimizing other disruptions of behavior, could be considered.

Acknowledgments

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