Speaking up: Killer whales (*Orcinus orca*) increase their call amplitude in response to vessel noise

Marla M. Holt and Dawn P. Noren
Marine Mammal Program, National Oceanic and Atmospheric Administration (NOAA), National Marine Fisheries Service (NMFS), Northwest Fisheries Science Center, 2725 Montlake Boulevard East, Seattle, Washington 98112
marla.holt@noaa.gov, dawn.noren@noaa.gov

Val Veirs
Department of Physics, Colorado College, Colorado Springs, Colorado 80903
vveirs@coloradocollege.edu

Candice K. Emmons
Marine Mammal Program, National Oceanic and Atmospheric Administration (NOAA), National Marine Fisheries Service (NMFS), Northwest Fisheries Science Center, 2725 Montlake Boulevard East, Seattle, Washington 98112
candice.emmons@noaa.gov

Scott Veirs
Beam Reach Marine Science and Sustainability School, 7044 17th Avenue NE, Seattle, Washington 98112
scott@beamreach.org

Abstract: This study investigated the effects of anthropogenic sound exposure on the vocal behavior of free-ranging killer whales. Endangered Southern Resident killer whales inhabit areas including the urban coastal waters of Puget Sound near Seattle, WA, where anthropogenic sounds are ubiquitous, particularly those from motorized vessels. A calibrated recording system was used to measure killer whale call source levels and background noise levels (1–40 kHz). Results show that whales increased their call amplitude by 1 dB for every 1 dB increase in background noise levels. Furthermore, nearby vessel counts were positively correlated with these observed background noise levels.

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1. Introduction

Marine mammals use sound for activities essential to survival and reproduction (NRC, 2003). They are often faced with the challenge of hearing these sounds in environments with noise from both natural and anthropogenic sources. Anthropogenic sound exposure in marine mammals has caused much concern, especially in cases that have extreme outcomes such as beaked whale mass strandings coinciding with naval midfrequency sonar exercises (NRC, 2003). While such exposure might lead to death, the occurrence of these sounds is relatively rare. Other sources of anthropogenic sounds in the ocean, such as motorized vessel traffic in coastal areas, are far more ubiquitous. Long-term exposure to prevalent anthropogenic noise may have deleterious effects on marine mammal populations, particularly those that frequent coastal regions where vessel traffic is concentrated. Although recent work in the laboratory has helped to define what sound pressure levels or sound exposure levels would likely result in auditory effects such as temporary threshold shift or masking in individuals, determining such effects in free-ranging marine mammals is challenging. Furthermore, information is lacking on what sound levels from specific anthropogenic sources result in behavioral responses in marine mammals and how these might have negative impacts on individuals and populations. This information is particularly crucial for informing policy designed to recover endangered populations.

Fishing-eating "resident" killer whales live in large and stable matrilineal groups, forage cooperatively (Ford and Ellis, 2006), and produce a variety of calls that have been described as discrete, variable, and aberrant (Ford, 1989). Discrete calls of killer whales are stereotyped and distinctive in structure as well as population-specific (Ford, 1987, 1989). Calls are thought to play key roles in social bonds among kin, mates, and other conspecifics. For example, call production and exchange is believed to function to maintain cohesion and coordination among group members when individuals are dispersed and foraging (Ford, 1989). Southern Resident killer whales (SRKWs), currently consisting of approximately 85 individuals among three (J, K, and L) pods, are listed as endangered (NMFS, 2005) and are found in coastal waters of Washington state and British Columbia. These inlands waters are important foraging areas for this population, particularly in the summer and fall where vessels, including ships, ferries, whale-watching boats, and private boats, are also prevalent. For example, the average number of vessels surrounding this population of killer whales in the summer is approximately 20 (Koski *et al.*, 2006) and it is not uncommon to find at least 50 vessels surrounding these whales during summer weekends and holidays. The frequency range of noise emitted from close vessels overlaps with the frequency range of killer whale calls (Ford, 1987; Erbe, 2002). Thus, this study aimed to address the impacts of motorized vessel noise on SRKW vocal behavior which is likely integral to their survival and reproductive success.

Individuals may compensate for background noise by changing their signal's amplitude, duration, repetition rate, and/or frequency. For example, SRKWs produced longer calls in the presence of vessel noise following a large increase in whale-watching boats (Foote *et al.*, 2004). Such vocal compensation is often interpreted as an antimasking strategy for high background noise levels. Our goal was to investigate call amplitude compensation (the Lombard effect), including measuring background noise levels and the number of nearby vessels of all types associated with these noise levels that were undocumented in previous studies. This approach is critical to elucidate how vessel noise affects the behavior of endangered killer whales and how they might compensate for changing levels of background noise to overcome masking by specific anthropogenic sources in their environment.

2. Method

We collected data in waters surrounding the San Juan Islands, WA off of a 8-m Pacific aluminum skiff, RV Noctiluca, over several days from August 23–September 4, 2007 as weather conditions and whale presence allowed it. Given the focus of this study on vessel noise effects, all measurements were made in sea states ranging from $\frac{1}{2}$ to 2.

When whales were sighted, the research vessel was positioned ahead and in the path of the whales (approximately 500–1000 m) to obtain on-axis recordings, the motor was shut down, and the recording equipment was deployed. We collected call and background noise data continuously while recording latitude and longitude, total motorized vessel numbers within 1000 m (measured by a laser range finder, Yardage Pro, Bushnell), and pod and identification (ID) of individual whales every 10 min. Individual whale IDs, distance from the research vessel (estimated with the range finder) and direction (visually estimated in 30 deg increments) of surfacing individuals relative to the research vessel were also taken opportunistically while recordings were made. Water temperature and salinity were measured at 5 m increments down to 30 m using a conductivity and temperature probe (YSI 30-M) at each location that acoustic data were collected.

Call source levels and background noise levels were measured from a calibrated omnidirectional hydrophone (Reson TC-4033) connected to a low-noise bandpass preamplifier (Reson VP2000, 1–100 kHz). A four-element hydrophone array (LabCore Systems) was used for localization that had a 20-m aperture and consisted of 5-m spacing between hydrophones 1–2 and 2–3 and 10-m spacing between hydrophones 3–4. The array was deployed vertically with hydrophone 1 at 5 m depth from the research vessel with a buoy and 10 kg weight. Signals were digitized using a MOTU Traveler (eight-channels, sampling rate 192 kHz), recorded using a customized version of Ishmael 1.0 (Mellinger, 2002), and stored as five-channel wave files on a PC laptop for analysis.

The range of a call was determined in Ishmael using time-of-arrival differences between hydrophone pairs in the array relative to the Reson hydrophone (hyperbolic localization). A sound speed of 1485 m/s was assumed based on average temperature and salinity profiles (MacKenzie, 1981). We determined the accuracy of Ishmael's range estimates and transmission loss in situ at two locations representative of where data were collected when no killer whales were sighted in the area over several days. Previously recorded S1 calls (see Ford, 1987) were projected using a sound source (Lubell LL 9816, 9 m depth) deployed from a dinghy at known horizontal distances. Received levels indicated that spherical spreading loss was an appropriate assumption. The largest resulting errors in source level occurred when the estimated range was relatively close (<40 m) or far (>400 m). This was expected because hyperbolic curves intersect at large enough angles to fix a location in the region that is neither too far from the linear array nor near its axis. At close ranges, range errors also results in larger source level errors given the logarithmic nature of transmission loss as defined in Eq. (2). Thus, we only included calls that were localized within an estimated range of 40–400 m. The subsequent range errors resulted in an average calculated source level error of 2.6 dB.

Call source level and background noise level measurements in dB_{rms} re 1 μPa were made over a 250 ms duration and a bandwidth of 1–40 kHz using SpectraPLUS v5.0 (Pioneer Hill) that was calibrated with 1 kHz pure tone projected in the water at a known received sound pressure level. The bandwidth was chosen based on both the mean hearing curve of captive killer whales (Szymanski *et al.*, 1999) and the observed frequency range of SRKW discrete calls when recorded on-axis. Background noise levels were taken just prior to a call (within 9 s) unless other overlapping whale sounds were present. In those cases, background levels measured just after the call (within 9 s) were used instead. Only source levels for stereotyped, discrete SRKW calls (Ford, 1987) are reported in the current study. The highest amplitude in dB_{rms} over a 250 ms duration within each call was chosen for calculating source levels. Call received levels (RL) were calculated by subtracting background noise levels from the signal logarithmically as follows:

$$\mathrm{RL} = 10 \log[10^{(\mathrm{dBsignal}/10)} - 10^{(\mathrm{dBnoise}/10)}]. \tag{1}$$

This was necessary given that the received signal level of the call was not always well above the corresponding background level. Call source levels were then calculated (in dB rms re 1 μPa at 1 m) as

$$\mathrm{SL} = \mathrm{RL} + 20 \log R, \tag{2}$$

where R was the range of the call estimated by Ishmael. Similar to Foote *et al.* (2004), call duration (to the nearest 0.01 s) was determined by using the cursor function of the sound analysis software program (SpectraPLUS v5.0). Linear regression analysis was used to determine relationships between call source levels and background noise levels, between call duration and background noise levels, and between background noise levels and $\log_{10}$ vessel counts. A t-test was also used to compare differences in call duration between low (<110 dB re 1 μPa) and high (>110 dB dB re 1 μPa) noise conditions.

3. Results and discussion

Call source levels and background noise levels were determined from recordings collected on four days (8/28/07, 8/29/07, 9/1/07, and 9/2/07). Only members of *J* pod were present on three of these four days, while all three pods (J, K, and L) were present on the other day. Call source levels in the 1–40 kHz band ranged from 133 to 174 dB re 1 μPa at 1 m with a mean of 155.3 dB re 1 μPa at 1 m (±7.4 SD). This mean was within 3 dB of stereotyped call source levels reported by Miller (2006) in Northern Resident killer whales despite differences in bandwidth, duration, and transmission loss assumptions used in making these measurements. Back-

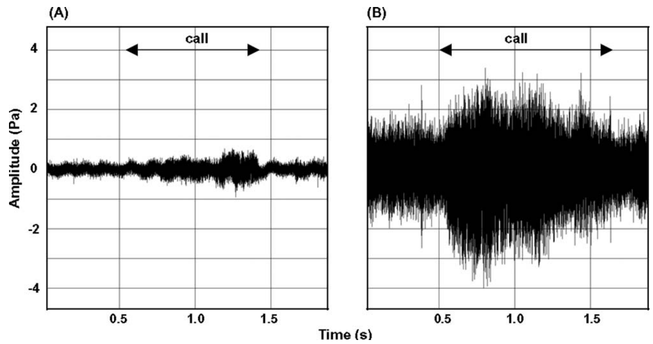

Fig. 1. Examples of killer whale calls recorded from an estimated range of 70 m in different noise levels based on dB_{rms} measurements between 1 and 40 kHz (a) S1 call in noise level of 100 dB re 1 μPa and (b) S1 call in noise level of 115 dB re 1 μPa. Arrows indicate the call in the time series.

ground noise levels in the 1–40 kHz band ranged from 98 to 123 dB re 1 μPa with a mean of 110.1 dB re 1 μPa (±4.1 SD). Nearby vessel counts ranged from 1 to 46.

We found a significant positive correlation between call source level and background noise level across all call types ($p<0.001$, $R^2_{adj}=0.25$, $n=274$). Since source levels and duration vary by call type (Ford, 1987; Miller, 2006) the subsequent analyses were restricted to one call type (S1) with the largest sample size. Examples of the S1 call recorded at similar ranges in relatively quiet and noisy conditions are shown in Fig. 1. Background noise levels explained approximately 50% of the variation in S1 call source levels ($p<0.001$, $R^2_{adj}=0.48$, $n=104$; Fig. 2(a)). Sample sizes were too small for similar regression analyses of other call types. The slope of the fitted regression line indicated that S1 call source level increased by approximately 1 dB for every 1 dB increase in background noise level (Fig. 2(a)). Furthermore, vessel traffic was clearly correlated with background noise levels ($p<0.001$, $R^2_{adj}=0.45$, $n=274$; Fig. 2(b)). Although it appears that S1 calls were produced at more or less equal source levels for corresponding background levels below 105 dB re: 1 μPa (Fig. 2(a)), the sample size below this background noise level was insufficient to precisely determine a threshold effect, and this observation warrants further investigation. Durations of these S1 calls ranged from 0.49 to 1.58 s with a mean of 0.95 s (±0.24 SD). Although the example in Fig. 1 shows a longer S1 call in the noisier condition, we found no significant slope or difference in call duration with changes in background noise level.

To our knowledge, these are the first data describing the Lombard effect in killer whales. Whales increased their call source level by 1 dB as background noise levels increased by 1 dB, at least over the range of background noise level measurements observed in this study. Schiefele *et al.* (2005) also reported a similar rate of vocalization level increase in response to a passing vessel in St. Lawrence River beluga. The upper range of background noise levels reported in the current study corresponded to approximately 45 nearby vessels. Such vocal compensation behavior by calling whales is presumably an effort to maintain adequate signal to noise ratios relative to listening whales.

Killer whales did not adjust their call duration over the range of background noise levels measured in this study. In contrast, Foote *et al.* (2004) reported a significant increase in killer whale call duration in the presence of vessel noise compared to in the absence of vessel noise. Differences in the results might be related to methodological differences between studies such as how vessel noise was assessed and/or the time span of data collection. Given that the current study did not include data from "no vessel noise" conditions, it is also possible that killer whales adjust call duration as a step response while they adjust call amplitude as a graded response to high background noise levels.

The results presented here show that as background noise from vessel traffic increases, killer whales adjust their vocal behavior by increasing call amplitude. The potential costs of

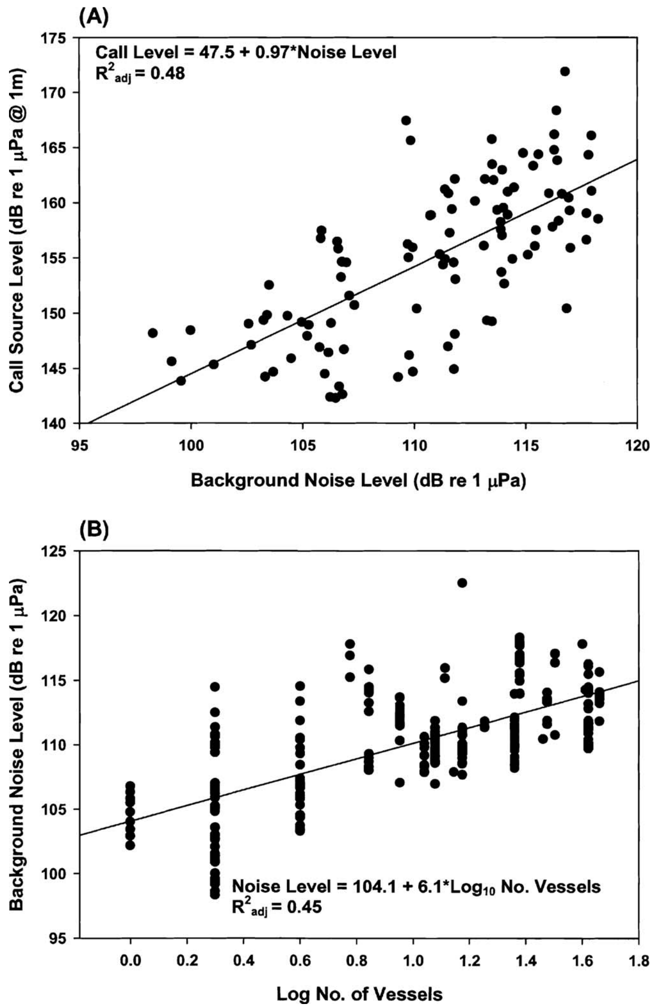

Fig. 2. (a) Killer whale call source level (S1 call type) as a function of background noise level, both based on dB_{rms} measurements between 1 and 40 kHz. (b) Background noise level as a function of the $\log_{10}$ number of vessels within 1000 m from the hydrophone.

such vocal compensation are important to consider. For example, increasing vocal output to compensate for noise might have energetic costs (Oberweger and Goller, 1991), lead to increased stress levels, or degrade communication among individuals which could affect their activity budget. At some level, background noise could also completely impede the use of calls by killer whales for communicative functions.

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