Spectral energy distribution in the discrete pulsed calls of free-ranging killer whales (*Orcinus orca*) changes in response to ambient noise levels.

by

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Abstract: Southern Resident killer whales frequenting the inland waters of British Columbia and Washington State are exposed to a diversity of anthropogenic noises, particularly from commercial and recreational motor vessels. This study examined spectral energy distribution in the discrete pulsed calls of free-ranging killer whales exposed to elevated ambient noise levels. Emphasis of the fourth harmonic of S1 stereotyped calls increased with broadband noise level (20 Hz–45 kHz), possibly as a secondary effect of increased call amplitude. Understanding the acoustic responses of these killer whales to noisy environments will inform management decisions intended to minimize human impact on this endangered population.

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1. Introduction

Marine mammals depend on acoustic signaling for a variety of tasks critical to their survival. Some cetaceans, including dolphins and humpback whales, use echolocation – a form of active sonar – to find and capture prey, navigate and avoid predators (Au, 2000; Stimpert *et al.*, 2007). Vocalizations and other acoustic cues are used by marine mammals for social coordination, identification of conspecifics, attracting mates and a variety of other purposes (Tyack and Miller, 2002). Anthropogenic underwater sound production continues to rise worldwide as merchant, commercial and recreational vessel traffic increases, presenting a potential challenge to acoustically-oriented marine species (NRC, 2005). Loud noise has been associated with elevated stress hormone levels and may have other harmful physiological effects (Romano *et al.*, 2004). High levels of anthropogenic noise may also result in hearing loss and/or masking of an acoustic signal (Erbe, 2002).

Considerable interest has been afforded the effects of anthropogenic noise on the Southern Resident community of killer whales, a group of 80 to 90 animals who frequent the Strait of Juan de Fuca, the southern Strait of Georgia and the adjacent inland waters of British Columbia and Washington State (Bigg, 1982; Ford *et al.*, 2000). In 2006 this population was listed as "endangered" under the U.S. Endangered Species Act due to concerns about population stability, prey availability and vessel impacts, among others (NMFS, 2008). These killer whales rely on echolocation in foraging for salmon, their primary prey item, and the use of discrete pulsed calls in foraging contexts suggests that these vocalizations might also be important for coordinating group hunting behavior (Ford, 1989; Barrett-Lennard et al., 1996; Ford, et al., 2000; Miller, 2002; Hoelzel and Osborne, 1986). Veirs and Veirs (2005) reported broadband received levels of between 95 and 130 dB (re 1 μPa) along the western side of San Juan Island in Haro Strait, a locale utilized heavily by these killer whales, between April 2004 and November 2005 (Hauser, 2006). Holt *et al.* (2009) reported noise levels (1-40 kHz) of 98 to 123 dB in the presence of the whale-watching fleet in the summer of 2007. Erbe (2002) suggested that a whale-watching zodiac (a small, rigid inflatable vessel driven with outboard motors) cruising at slow speed might have a masking effect for killer whales within 1 km.

A variety of strategies have been used by cetaceans to mitigate the interference of noise in their communication. An increase in call duration has been observed for humpback whales exposed to low-frequency active sonar (Miller *et al.*, 2000). Foote *et al.* (2004) showed an increase in the duration of killer whale calls in the presence of boats which they attributed to masking-avoidance, but such a response could not be confirmed by Holt *et al.* (2009). Thomas (1999) suggested that Antarctic killer whales shift the frequencies of their calls to avoid competition with leopard seals (*Hydrurga leptonyx*) for acoustic space, and beluga whales in the St. Lawrence River estuary have exhibited a similar response when exposed to boat noise (Lesage *et al.*, 2006). Marine mammals may also increase the amplitude of their calls to be heard over noise – a response known as the 'Lombard effect' – as has been observed in Beluga whales and killer whales (Scheifele *et al.*, 2005; Holt *et al.*, 2009).

Although a broadband increase in call amplitude in response to boat noise has been described for this population (Holt *et al.*, 2009), an examination of spectral parameters of calls produced in varying noise states has not been published. Miller (2002) showed that caller sex can impact the relative power of certain harmonics within discrete pulsed calls, probably as a correlate of body volume, but that such ratios do not change with caller orientation. Fine frequency discrimination has been shown in bottlenosed dolphins (*Tursiops truncatus*), including the ability to process information at multiple frequencies simultaneously (Thompson and Herman, 1975; Helweg *et al.*, 2003). False killer whales (*Pseudorca crassidens*) are able to discriminate small changes in the relative power of harmonics (Yuen et al., 2007). Spectral features may be used for individual or sex recognition, or convey other information about the state of the caller (Miller, 2002; Wilczynski *et al.*, 1995). In humans, increased glottal pressure (due to vocal effort) results in a disproportionate increase in power at higher frequencies, an effect that may be more important than overall sound pressure level in the perception of speech intensity (Sunderberg and Nordenberg, 2006; Eriksson and Traunmuller, 1999).

The present study examined the spectral distribution of energy in the harmonically rich pulsed calls of Southern Resident killer whales exposed to a range of noise states. As policy-makers consider strategies aimed at reducing human impacts on this endangered population, a nuanced understanding of how these animals respond to noise, and mitigate its effects, will inform a balanced assessment of costs imposed on these animals by vessel traffic. Such knowledge may also provide a basis for evaluating noise impacts as they occur through passive acoustic detection and analysis. Additionally, this study served as a pilot project to evaluate the feasibility of performing acoustic field research from commercial whale watching platforms.

2. Methods

Recordings of SRKW calls in the presence and absence of various compositions of vessel traffic were made using a single calibrated hydrophone (at a depth of about 15 m) and a Fostex FR-1LE digital recorder (24 bit/192kHZ) from onboard two commercial whale-watching vessels, M/V *Olympus* and M/V *Glacier Spirit*. Data collection began in late May and ended in early August, 2008. The hydrophone had an omnidirectional flat response (± 3 dB) to about 45 kHz. Calls were recorded when whales were within 200 m of the vessel and any large noise sources were at least 25 m away, so as to minimize bias in the characterization of the animal's noise environment. All recordings were made in sea states less than 2 on the Beaufort scale.

Call spectrograms were generated in Raven Pro 1.3 (Cornell Lab of Ornithology, http://www.birds.cornell.edu/raven) using a window size of 20.8 ms. Only S1 stereotyped calls, after Ford (1987), were analyzed. Five spectrogram slices (evenly spaced in the time domain) were taken for the first syllable of each call, and the powers of the first four harmonics were averaged over these samples (Fig. 1). In the case that a harmonic was not detectable above the ambient noise, the average noise level in the range 50 Hz above and below the expected frequency for that harmonic (consistent with observed side-band intervals) was taken as its maximum possible value (and thus the most conservative estimate). Noise level was assessed as the broadband (20 Hz to 45 kHz) RMS amplitude over a 0.2 s interval immediately preceding each call. Each call was assayed for changes in the relative intensity of harmonics as a function of ambient noise level.

3. Results and Discussion

Calls were selected for analysis not only on the basis of their type but also on the ability to isolate them from other signals (calls and echolocation clicks) and artificial noise (e.g. abrasion of the hydrophone cable). Consequently, calls used in the final analysis were from recordings made on three days (20 July, 26 July and 1 August, 2008), during which only members of J pod were encountered. Broadband noise levels (20 Hz – 48 kHz) varied from 103 to 130 dB re 1 μPa, most of which was explained by variation in the 20 – 500 Hz frequency range ($y=1.1765x-1.2602$, $p < 0.001$, $R^2=0.98$, $n=27$, data not shown). Although audiograms for killer whales have not been produced below 1 kHz, Johnson (1967) reported a hearing threshold of between 95 and 130 dB below 1 kHz for bottlenosed dolphins, suggesting that the low-frequency noise levels observed in this study are also detectable by killer whales.

The power of the fourth harmonic relative to that of the fundamental increased with noise level in S1 calls (Fig. 2). This was not observed for the second and third harmonics (Fig. 3). Because it was not possible to determine the distance of the caller from the hydrophone the received sound level may not precisely reflect that experienced by the calling whale. Since care was taken to record only when within 200 m of the calling animals, however, the values used here are assumed to be good estimates.

To rule out the effect of pulse repetition rate (represented in the frequency of the fundamental) on harmonic emphasis, the ratio of the power of the fourth harmonic to the fundamental was plotted against the frequency of the second harmonic. The second harmonic was chosen because the fundamental was not always discernable, and the sideband intervals were stable within each call. No such correlation was found. Furthermore, the frequency of the second harmonic (1969 Hz to 2625 Hz) was not correlated with noise level, consistent with Holt *et al.* (2009).

Emphasis of the fourth harmonic in calls made by this population has been reported by Miller et al. (2007), particularly for females, which they suggested might be a product of frequency-specific resonators within the whale. Although caller-receiver orientation was shown by Miller et al. (2007) to affect the relative power of high-frequency and low-frequency components in two-voice calls, the relative power of harmonics in calls with only low-frequency components (as were those used in the present study) was unaffected by orientation.

A large body of work exists on the relationship between vocal effort and spectral balance (the relative energy at higher frequencies to that at lower frequencies) in human speech. Increased lung pressure results in greater asymmetry of glottal pulse, disproportionately enhancing higher frequencies (Fant and Lin, 1988). There now seems to be some consensus that killer whales vocalizations are produced in the nasal apparatus rather than the larynx (Cranford, 2000). Air flowing through the nasal passages acts to part a pair of ‘phonic lips,’ producing pulses in a fashion similar to those produced in the larynx of terrestrial mammals (Cranford, 2000; Tyack and Miller, 2002). It is therefore conceivable that the observed shift in energy to the fourth harmonic is analogous to the increase in spectral balance observed in humans, described above. Increased pressure behind the phonic lips due to greater call amplitude, as reported by Holt *et al*. (2009) may result in a pulse asymmetry similar to that described for humans (Fant and Lin, 1988). On the other hand, the lack of a relationship between enhancement of the second and third harmonics and noise level may be more consistent with the effect of frequency-specific resonators proposed by Miller et al. (2007). It is possible that a combination of pulse asymmetry and signal filtration may underlie these results.

During the closing remarks of the 2006 NOAA Fisheries Services Southern Resident Killer Whale Symposium a representative of the Whale Watch Operators Association Northwest made a statement to the general assembly, offering the use of deck space on commercial whale watching platforms to working scientists. To our knowledge this is the first published study of that kind, and illustrates the feasibility of such a model for field research.

Conclusion

Increased ambient noise is correlated with a spectral energy shift in the discrete pulsed calls of Southern Resident killer whales. Similar analyses for other call types should be conducted to corroborate this finding. If this response is found to be typical, these results may serve as a basis for characterizing the calls of vocally taxed killer whales. With such knowledge in hand an observer would be better equipped to determine when, and to what extent, these animals are impacted by anthropogenic noise. Changes in the relative intensity of harmonics might be used by whale watchers for real-time detection of acoustic interference, making them better equipped to regulate their own behavior.

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Figures

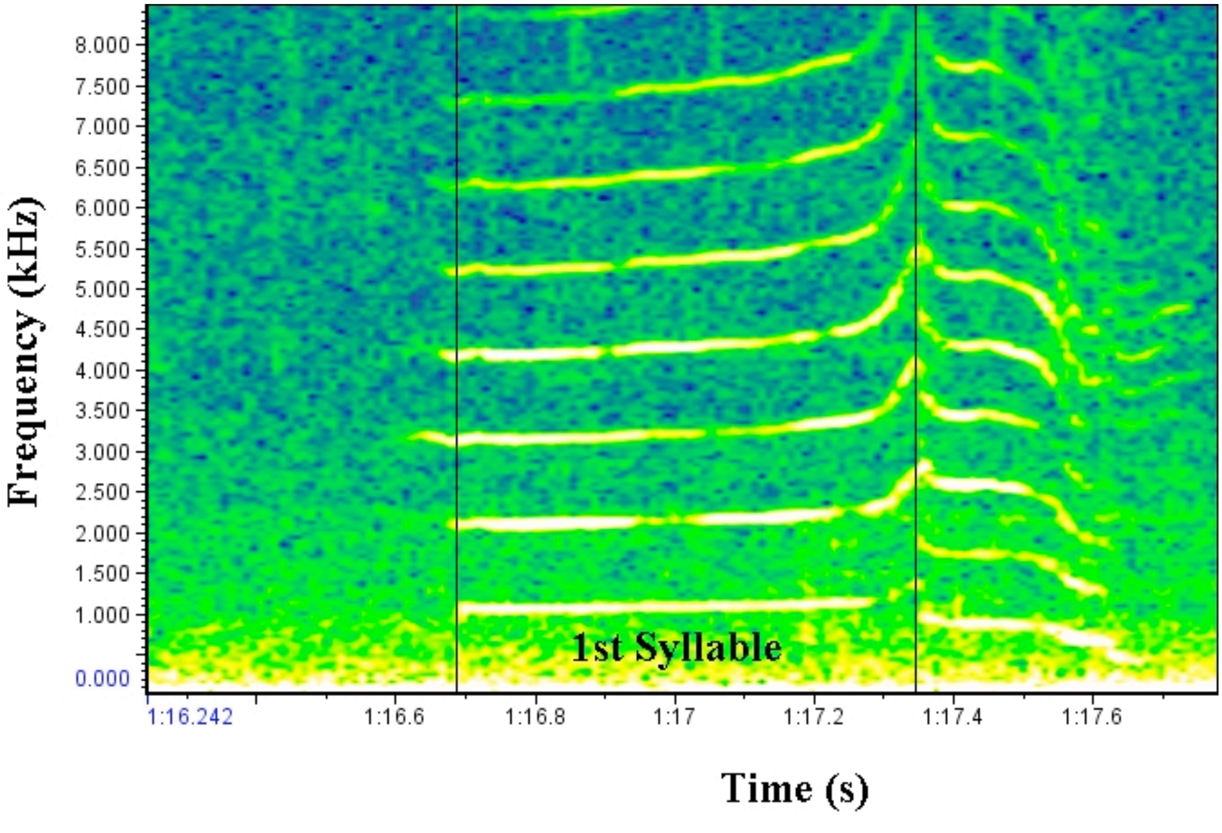

Figure 1. S1 discrete pulsed call produced by a Southern Resident killer whale. Analyses presented here concern the first syllable, depicted here between the vertical lines.

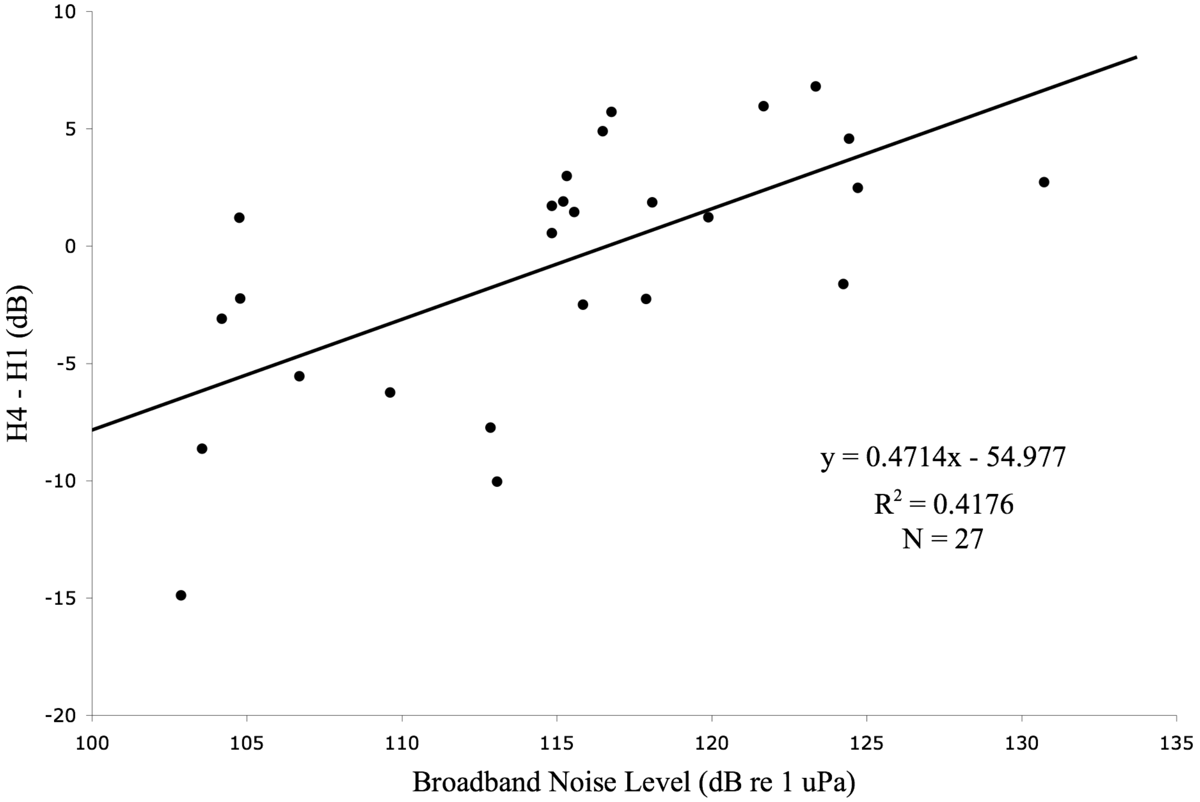

Figure 2. The ratio of powers of the fourth harmonic and the fundamental as a function of broadband noise level between 20 Hz and 45 kHz (*N* = 27).

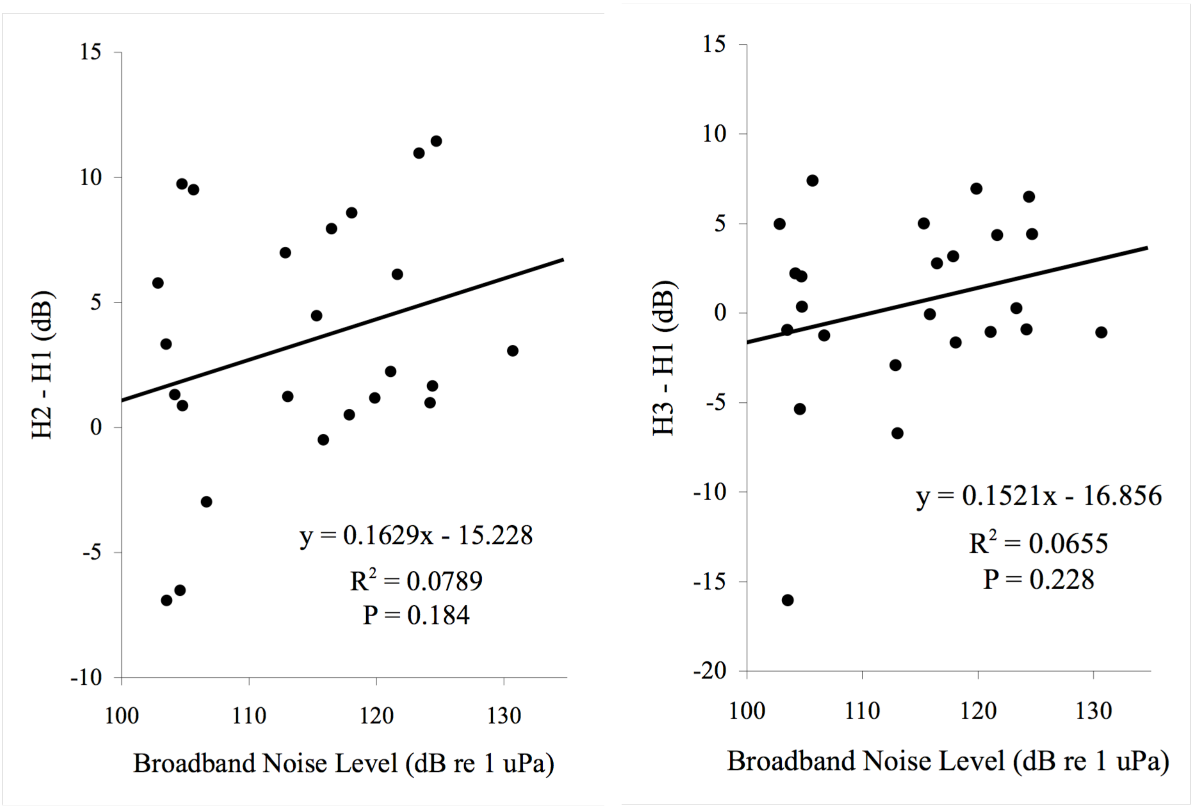

Figure 3. The ratio of powers of the second and third harmonics to the fundamental as a function of broadband noise level between 20 Hz and 45 kHz ($N = 27$).