Proceedings of Meetings on Acoustics

Volume 19, 2013 http://acousticalsociety.org/

ICA 2013 Montreal
Montreal, Canada
2 - 7 June 2013

Animal Bioacoustics
Session 4pAB: Animal Vocal Modification in Noise

4pAB5. Modification of humpback whale social sound repertoire and vocal source levels with increased noise

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High background noise is an important obstacle in successful receiver signal detection and perception of an acoustic signal. To overcome this problem, animals modify acoustic signals by increasing the repetition rate, duration, amplitude, or frequency range of the signal. Humpback whales are the most vocal of the baleen species in that they use a wide and varied catalogue of social sounds. More than 36 different sound types (vocal sounds and sounds from energetic surface behaviours) were found during a three year study on migrating humpback whales. During periods of high wind noise, humpback whales modify both their acoustic repertoire as well as vocal signal properties. We found that humpback whale groups gradually switched from primarily vocal to primarily surface-generated communication in increasing wind speeds and background noise levels, but kept both signal types in their repertoire. We also found evidence of the Lombard effect, in that in increased wind-dominated background noise levels, humpback whale groups tended to increase the amplitude of their vocalisations. Determining how whales modify their vocal behaviour in increasing levels of background noise will give us an important insight into how they might cope with increasing levels of anthropogenic noise.

Published by the Acoustical Society of America through the American Institute of Physics

Received 22 Jan 2013; published 2 Jun 2013

THE DUEL NATURE OF HUMPBACK WHALE ACOUSTIC SIGNALING

Speech changes due to noise are collectively called the Lombard effect, where signalers generally modify vocal characteristics such as level, pitch and/or rate of signal production in a noisy environment to improve signal detection (Lombard, 1911). Most studies designed to test for the Lombard effect in animals look for an increase in signal level in response to increased broadband background noise levels. This effect has been found to occur in birds (Cynx *et al*., 1998), cetaceans (Holt *et al*., 2009; Parks *et al*., 2010; Noad *et al.,* 2012) and primates (Brumm *et al*., 2004). Rather than increase the source level of a signal, another way to mitigate the effect of increasing background noise could be to enhance primary signals or signaling behavior with a secondary signal or signaling behavior. To do this, the signaler requires two different acoustic signals or signaling behaviors that perform the same, or complimentary, function, but can be interchanged depending on the level of background noise. This secondary signal (or signaling behavior) should have properties that allow better signal reception and perception in a noisy environment compared to the primary acoustic signal.

Humpback whales are one of the most vocal of the baleen whale species in that they 'sing' as well as produce non-song vocal sounds. Humpback whale song is a male-only signal (Glockner, 1983; Baker, 1994), defined as being long, complex, repetitive and highly stereotyped (Payne & McVay, 1971; Payne *et al.,* 1983; Cato, 1991). Non-song social vocalizations in humpback whales are not clearly structured like song as they have little serial patterning and are heard as single sounds or in short bursts (Tyack, 1983; Tyack & Whitehead, 1983; Silber, 1986). Humpback whales utilize an extremely variable catalogue of social vocalizations, from almost infra-sonic 'grumbles' to high frequency 'chirp'–like sounds (Dunlop *et al*., 2007) and these sounds are apparently used by both sexes and in closer-range communication compared to song (Dunlop *et al*., 2008).

Sounds generated as a whale interacts with the surface may also be used as acoustic communication signals if they are audible by the receiver. They include sounds from behaviors such as 'breaching' (leaping out and slamming into the water), 'pec slapping' (repeatedly slapping one or both pectoral flippers on the water surface) and 'lobtailing' or 'fluke slapping' (thrashing the flukes onto the water surface) (Whitehead, 1985). Although the function of surface behaviors in humpback whales is not well understood, it has been suggested that breaching especially may have an important signaling role due to the loud splash made (Clark, 1990; Herman & Travolga, 1980; Norris & Møhl, 1983) and may be used to maintain contact within a dispersed group (Payne, 1978). Pectoral flipper and fluke slapping may also serve a communicatory function (Clapham, 2000; Deakos 2002; Dunlop *et al*., 2008; Noad, 2002; Nachtigall *et. al.,* 2000; Silber, 1986; Thompson et al., 1986; Wahlberg *et al.,* 2002). Therefore, humpback whales may use two different types of communication signal; vocal acoustic signals which convey detailed information and surface-generated sounds which may convey less information.

Humpback whales, like all marine mammals, are exposed to many sources of noise; background shipping, biological, wind and waves and surf. Wind-dependent noise is generated by surface waves breaking. Previous studies found that humpback whales changed their signaling repertoire from primarily vocal to primarily surface-generated sounds in response to increasing levels of wind-dominated background noise (Dunlop *et al*., 2010) as well as increased the source level of their social vocalizations (Noad *et al*., 2012). What was notable from the two studies was that despite the large signal excess of the social vocalizations (Noad *et al*., 2012), humpback whales still used two different strategies apparently to compensate for the effects of increased levels of background noise. This paper will discuss possible reasons for this duel change in acoustic behavior.

Modeling the received SNR of social vocalizations in low, mid and high noise

The signaler must produce the signal at an appropriate intensity for the target receiver to detect and decode it, and this may vary with distance to the receiver (Wiley & Richards, 1982). Vocal levels attenuate during transmission and, as the distance from source to receiver increases, the received signal level generally decreases. To compensate, animals may vocalize at higher levels when signaling to a distant receiver to communicate more clearly (Brumm & Slater, 2006). Therefore, as levels of noise increase, the signaler should increase the level of vocal signals to maintain a constant signal excess regardless of noise. One way to test for this would be to measure the signal-to-noise ratio (SNR) of vocal signals at the receiver in different noise conditions to see if the SNR remains constant regardless of noise.

Data were collected as part of the Humpback Acoustic Research Collaboration (HARC) during the September/October southward migrations of 2002 – 2004 and 2008 (for detailed methods see Noad *et al*., 2004). The study site was Peregian Beach, 130km north of Brisbane on the east coast of Australia (26° 30'S, 153° 05'E). Wind-dominated background noise in the study area ranged from 88 to 103 dB *re* 1μPa (measured as a broadband SPL between 40 Hz and 2 kHz). A typical low noise level for this study site was 90dB *re* 1μPa (in wind speeds ranging from 6 to 10 knots), a typical mid-noise level was 95 dB *re* 1μPa in winds ranging from 11 to 15 knots and a typical high noise level was 100 dB *re* 1μPa in winds ranging from 16 to 20 knots. Average social vocalization source levels of whales vocalizing in low, mid- and high noise were used to estimate the received level of these sounds at various distances ranging from 200 m to 6 km in each of the noise conditions. The received levels were calculated using the transmission loss model developed for the study site (for further details on calculating source and received levels within the study site see Dunlop *et al.,* 2013). Using typical broadband noise levels in low, mid and high noise, the received SNRs were then estimated for each distance for each noise level (FIG. 1).

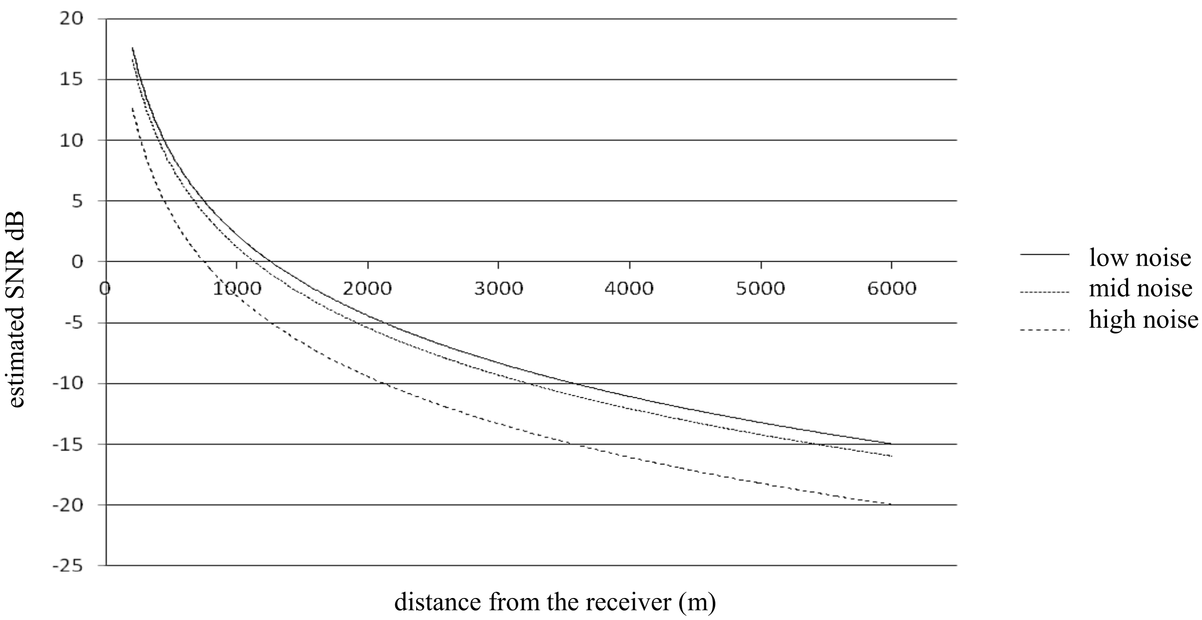

FIGURE 1. The received signal-to-noise ratio (SNR) of social vocalizations at distances ranging from 500 to 6000 m from the receiver. SNRs were estimated using typical signal (social vocalization) source levels and noise levels in low, mid and high noise conditions.

The graph illustrates that the received SNR for each distance was similar in low and mid noise but lower in high noise. In other words, it seems that whales compensated for increased background noise by increasing the source levels of social vocalizations to maintain a consistent signal excess in mid noise compared to low noise, but did not maintain this signal excess in high noise. Therefore it seems that successful vocal communication would become more difficult in higher noise, especially as the distance of the receiver increases. One strategy to counteract this effect would be to modify acoustic communication behavior in order to enhance signal detection in high noise and this could be a reason for the change to utilizing surface-generated sounds found in humpback whales.

Why switch to surface-generated sounds?

The change in acoustic signaling behavior in humpback whales from social vocalizations to surface-generated sounds suggests that surface-generated sounds can enhance vocal communication in some way. It could be that surface-generated sounds are less likely to be confused in high noise, or are used as non-vocal 'attention-getting' signals (Dunlop *et al.,* 2010). Alternatively, it could be that surface-generated sounds have higher source levels than social vocalizations. Although social vocalizations had similar source levels compared to surface-generated sounds (unpublished data), peak levels of surface-generated sound source levels were about 6 dB higher compared to social vocalizations (measured as peak-to-peak by taking 20 log of the greatest change from positive to negative pressures in any cycle in the wave form). Peak levels of surface-generated sounds did not fall below 160 dB *re* 1µPa@1m (FIG. 2).

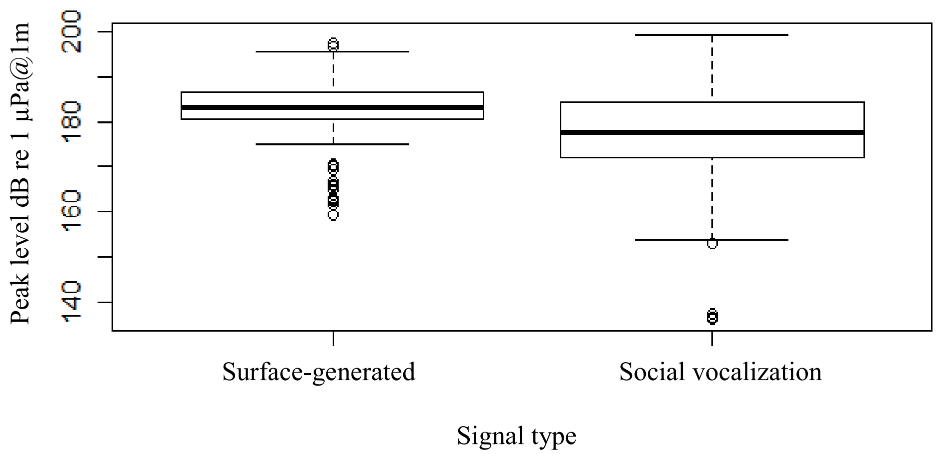

FIGURE 2. Boxplot of peak levels of surface-generated sounds and social vocalizations measured from humpback whale groups within 2 km of the array

CONCLUSIONS

It is becoming increasingly apparent that social communication in humpback whales is a complex system. In these studies, only wind noise was considered. Further studies are required to determine how they respond to increases in anthropogenic noise as well as their own chorusing noise from singing whales. What has been shown in this study is that humpback whales do employ various methods for coping with large variations in background noise (about 20 dB in this study site). Whether there is some upper limit to the response to increased levels of noise is another question.

ACKNOWLEDGMENTS

The authors thank everyone involved in the Humpback Acoustic Research Collaboration (HARC), in particular the numerous volunteers who donated their time and energy to this project. We also thank David Paton for his invaluable field expertise and Eric Kniest for his continued support in the development of Cyclopes. This work was supported by the US Office of Naval Research, the Australian Defence Science and Technology Organisation and the Australian Marine Mammal Centre.

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