An investigation of frequency shifts in the echolocation clicks of Southern Resident killer whales (*Orcinus orca*) in response to high levels of ambient noise

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I. INTRODUCTION

Killer whales (*Orcinus orca*) belong to the suborder of cetaceans that includes toothed whales, or odontocetes. Typically, odontocetes are highly social, evidenced by their tendency to organize themselves into groups, and their high levels of vocal activity when such groups are formed. Killer whales follow this pattern, occurring in social groups called *pods*. These pods may consist of as many as 50 individuals, though average pod size ranges between 2 and 15 whales (NMFS 2008, II-10). Each pod is made up of one or multiple closely related *matrilines*. A usual matriline is comprised of a female, her male and female offspring, as well as the offspring of her daughters (NMFS 2008, II-11). Individuals within a matriline are thus very highly related, and rarely separate from the main group. Matrilines associate more closely with matrilines of the same pod than with those of other pods. Pods are grouped into *clans* by their degree of relatedness, and, in turn, clans that associate with one another regularly form *communities*. The community of whales featured in this study is the Southern Resident community (SRKW) that inhabits Pacific Northwestern waters during the summer months. Their distinction from other killer whale communities is apparent in many aspects, including, but not limited to their vocal dialect.

Killer whales, and all odontocetes for that matter, exhibit three general vocalizations: whistles, clicks, and pulsed calls (NMFS 2008, II-14). Whistles are tonal sounds that contain dominant frequencies at 8.3kHz on average (NMFS 2008, II-14); pulsed calls are the most frequent of killer whale vocalizations (NMFS 2008, II-14), and highly distinguishable (discrete) calls, key to establishing dialects among varying levels of social hierarchy. Echolocation "clicks" are believed to be used for navigation and localization of prey, and possibly also for communicating during foraging events or otherwise. It is possible that high levels of anthropogenic sound (i.e. dredging, pile driving, drilling, sonar, commercial boating, etc.) are capable of masking killer whale calls, including the echolocation clicks that are vital to the feeding success of killer whales (NMFS 2008, II-14).

Christine Erbe (2002) investigated the underwater noise of whale-watching boats and its potential effects on killer whales that resided in the Juan de Fuca and Haro Straights in southern British Columbia and northern Washington. It was found that boat source levels ranged from 145 to 160 dB and were audible to killer whales within 16km. Depending on the received level and frequency nature of that noise, the calls of the whales could be masked. Masking occurs when the bandwidth of the background noise of sufficient amplitude overlaps with the frequency bands of the call. It is suggested in

Erbe's paper that shifting call frequencies outside of interfering range (i.e. critical bandwidth) would result in better detection of those calls.

Odontocetes have indeed shown on multiple occasions the ability to alter clicking behavior to suit the needs of their lifestyle. Transient killer whales, for example, use clicks only rarely while foraging, whereas resident killer whales are believed to use a high proportion of clicks to localize their prey items in addition to communicating while foraging (Ford 1989). This disparity comes due to differing prey items between residents and transients. While residents feed primarily on salmon, transients tend to feed on marine mammals, and while salmon are behaviorally unresponsive to characteristic echolocation frequencies (Hawkins and Johnstone 1978), most marine mammals have the ability to detect killer whale echolocation. Thus, as a hunting strategy, transient killer whales significantly decrease the amount of clicks they employ while seeking prey (Deecke et al. 2004; Barrett-Lennard et al. 1994). Furthermore, there is evidence that different click frequencies are employed among killer whale ecotypes (Foote 2008). Offshore killer whales for instance, display minimum frequencies that are much higher than those of either resident or transient ecotypes, presumably due to the high levels of low-frequency background noise they endure created by the higher wind speeds in their environment (Foote 2008).

Sperm whales (*Physeter macrocephalus*) have been shown to shift the frequency of their clicks from 10 kHz to 15 kHz as the depth of descent increases, though the exact reason for such a shift is unknown (Thode et al. 2002). C. Kamminga and J.G. van

Velden showed that the dominant frequency in *P. crassidens*, a pelagic dolphin, was around 28 kHz. Even so, occasional two-component sonar clicks demonstrated energy around 100 kHz in that study.

A study carried out by Au Whitlow (et al. 1984) demonstrated the ability of a beluga whale (*Delphinapterus leucas*) to shift its biosonar to higher frequencies after it was moved from an area of low ambient noise, to that which expressed comparatively high levels of ambient noise. The animal shifted its sonar peak (most significant) frequency from 40-60 kHz in San Diego Bay, California to frequencies between 100-120 kHz when they moved to Kaneohe Bay, Hawaii (ambient noise levels were 12-17 dB greater in Kaneohe Bay).

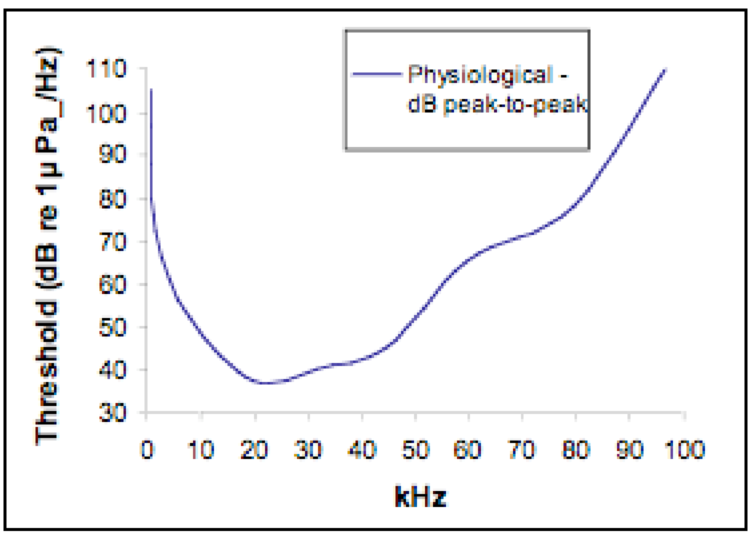

Figure 1 – the audiogram of a killer whale as shown by Szymanski et al. 1999 (taken from Hunt 2007)

Orca echolocation is unusually low in frequency (~25 kHz)(Richardson et al. 1995), almost an entire octave lower than bottlenose dolphins (*Tursiops trucatus*)(Au et al.

2004). The killer whale audiogram (Fig.1), shows that the whale's most sensitive hearing frequency (~20kHz) closely corresponds with the lower peak found in orca echolocation. Unfortunately, according to graphs produced by Tim Hunt (2007), many of the boats that Southern Residents commonly encounter exhibit energy levels between 10-20kHz that have the potential to mask typical echolocation calls. However, most killer whale clicks display bimodal distribution, resulting in another peak in energy at higher frequencies, between 40-60kHz (Au et al. 2004), a feature of the click that provides a possible outlet for masking avoidance.

The purpose of this investigation is to divulge correlation between killer whale echolocation clicks and the amplitude of interfering background noise they experience. With the ability to shift frequency in response to environmental changes clearly present in odontocetes, and taking into account the immediate foraging benefits it could entail, it would not be surprising to discover a compensatory change in the nature of Southern Resident clicks when background interference is present. Due to the bimodal nature of killer whale clicks, such compensation could possibly be achieved by shifting the lower peak frequency of the click (located ~25kHz) to higher frequencies, or by increasing the energy that is devoted to the high frequency peak (located ~40-60kHz).

Thus, I hypothesize that killer whale clicks will display peak frequencies that are significantly higher (in frequency) than those found in typical click spectrums. Further, in the event that this pattern is not seen, I hypothesize that the high frequency peak of clicks will show an increase in amplitude as interfering background noise increases in amplitude.

II. METHODS

A hydrophone array consisting of four hydrophones was towed off port stern of the research vessel (Fig. 2). A high frequency hydrophone (HF) was towed off the starboard stern of the same vessel in manner that closely resembled that of the array. The HF was incorporated into the projects of other students on the research vessel which involved localization. Therefore, the intention was to deploy the HF at the same distance behind the boat as the first hydrophone in the array by attaching a 12lb weight ~2m from the hydrophone and further extending ~7.5m of hydrophone cable before securing it to the boat. SRKW vocal activity was recorded opportunistically using the HF configuration connected to a 2k sound device.

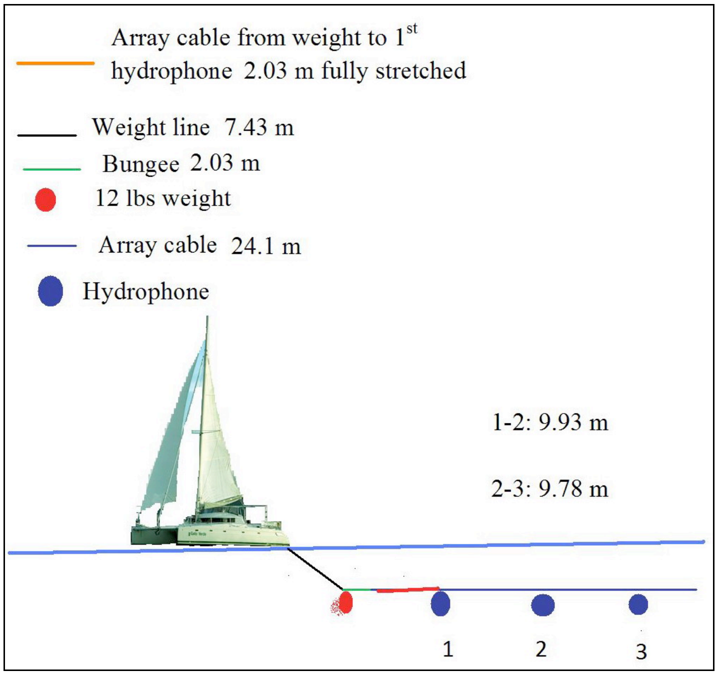

Figure 2 – The Gato Verde (research vessel) and the hydrophone array deployed off the port stern. The HF is deployed off the starboard stern in a similar fashion (used with permission of Dominique Walk).

Ambient noise and echolocation clicks were recorded in and around North Pacific inland waters (Straight of Juan de Fuca, Haro Straight, Rosario Straight, etc.). Due to the likelihood that multiple boats contributed to the overall background noise, calculating source levels of the background noise is impractical. For this reason, recorded background amplitudes are used as the amplitudes experienced by the whales (received level).

Recordings were made during the month of May in 2008. Days were variable in the number of recordings they yielded, and each recording was variable in length of time. This depended heavily upon what was heard through the hydrophone (i.e. recordings lasted roughly as long as vocalizing activity was exhibited). Each recording, in turn, was broken down into one-minute excerpts for easy access to valuable minutes. Since echolocation clicks were so liberally produced, and considering the time limitations of this study, only a handful of these excerpts were analyzed. From each one minute except that was selected, five clicks were analyzed for their peak frequency (*f*p), their next significant peak (*f*p2), and the amplitude ratio between the two. During one recording episode, an individual belonging to J-pod known as J-1 (Ruffles), was recorded in isolation from any other individuals. This is the only instance of recording clicks from a known individual in this study. While it is known that members of J-pod produced all other clicks, the specific individuals that produced the clicks were not known.

In addition to analyzing clicks, the background noise present during the generation of those clicks was also analyzed. Only the sound that occurred between 15-25kHz was analyzed, and for multiple reasons. Firstly, this frequency band includes the frequency that killer whales are most sensitive to. This frequency consequently corresponds with the peak frequency of the echolocation clicks they emit. Most importantly, above 10kHz, this is the frequency band within which background noise tends to be most significant. Therefore, shifting peak frequency out of that range should result in masking avoidance. Using Val Veirs Beam Reach Sound Analyzer (v. May '08), background noise spectrums and click spectrums were generated, and the aforementioned measurements were extracted from them. Additionally, since not all clicks display bimodality, the average peak frequencies of modal and bimodal clicks were compared.

I expect that as background amplitudes increase within the frequency band of 15-25 kHz, clicks will produce spectrums that show compensatory frequency patterns.

Specifically, I expect that one of the following will be found in click spectrums: peak frequencies will shift to higher frequencies, or low-peak to high-peak ratios will decrease.

III. RESULTS

The relationship between peak frequency and background noise was not significant in either the absence or presence of J-1 clicks (Fig 3.). The ratio of *f*p to *f*p2 grew significantly as background noise increased (p=0.002, $F1,82=10.04$), but only when J-1 clicks were omitted. This ratio increase is mostly due to an increase in the amplitude of the low frequency peak, however the high frequency peak does slightly decrease as background noise increases.

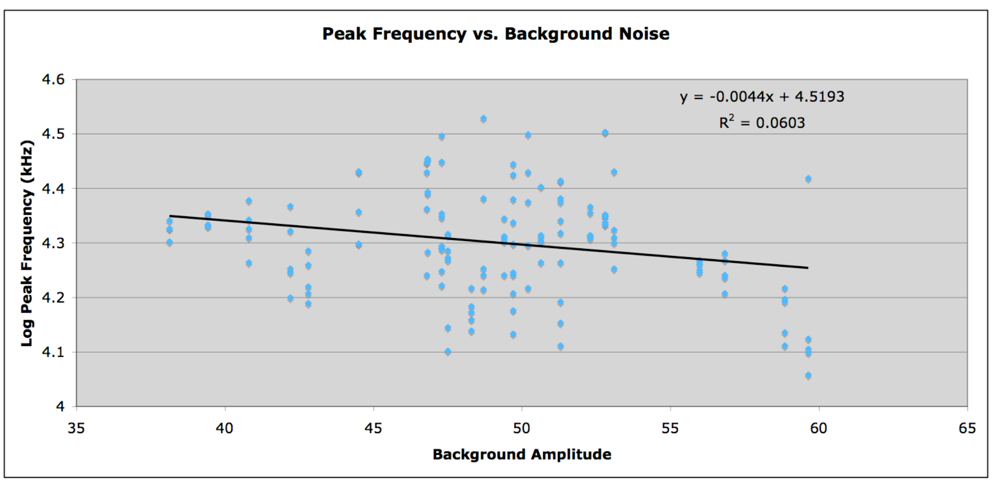

Figure 3 – *f*p of each click plotted with respect to the background amplitude at which it was generated. This graph includes J-1 data.

Multiple peaks were observed in 102 of the 141 clicks investigated. They displayed peak frequencies that were lower (19669.3Kz) than the peak frequencies of modal clicks (22654.6Hz). Furthermore, modal clicks were emitted at an average background amplitude (45.9dB) that was lower than bimodal clicks (50.3dB) (Fig). Excluding J-1 data, the average peak frequency of bimodal clicks is raised to 20435.2Hz, and the average background noise at which bimodal clicks are generated becomes 48.5dB. The exclusion of J-1 data does not affect modal averages, as that individual did not generate any modal clicks at the time of recording.

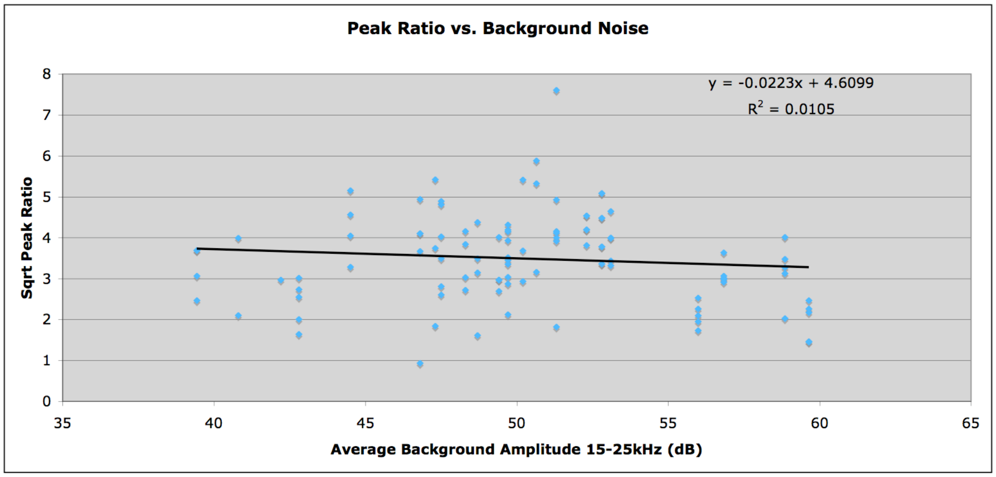

Figure – the amplitude ratio of *f*p to *f*p2 with respect to the background amplitude at which the bimodal click was produced. This graph includes J-1 data.

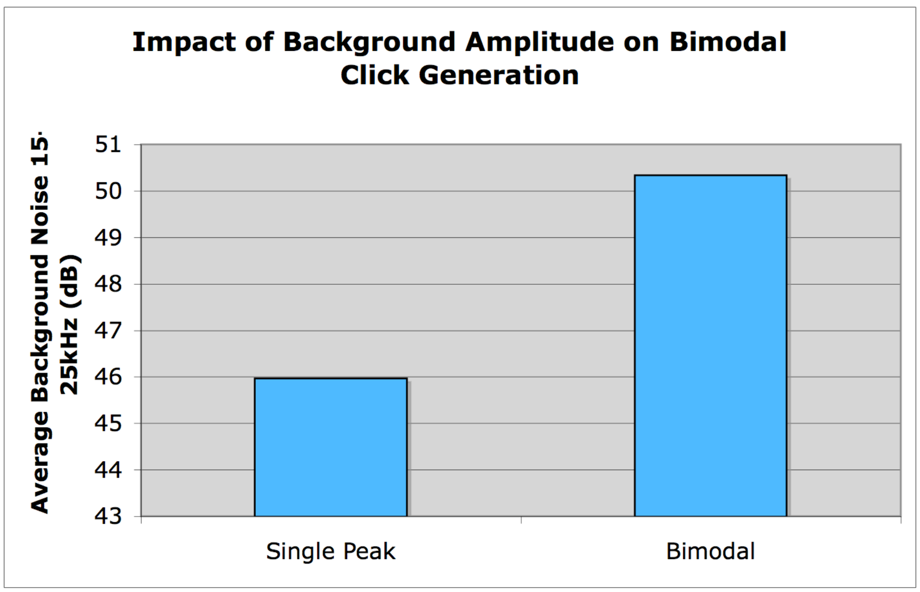

Figure – average background noise at which each type of click is emitted.

Using a binary logistic regression, the impact of background noise on the generation of bimodal clicks was tested. It showed that bimodal clicks were more likely to be generated as background noise increases (coef=0.18; Z=4.07; $p<.0001$; odds ratio=1.2), which was also true when J-1 data was omitted (coef=0.15; Z=3.02; p=.003; odds ratio=1.16). Additionally, the second most significant frequency assumed an average of 38922.2Hz.

IV. DISCUSSION

No significant shift was found in the peak frequencies of Southern Resident echolocation clicks when background noise amplitudes increased. Furthermore, the ratio of the low peak to the high peak only increased significantly in the absence of J-1 data (p=.014; $F_{1;140}$=6.18). This is an effect of an increase of the low frequency peak in relation to the high frequency peak. When that data is included, this ratio decreases, though not significantly. These results do nothing to support the original hypothesis that peak frequencies will shift when high levels of interfering noise are presented. However, there are some interesting relationships found in this study that imply that Southern Residents may be relying on the high frequency component of their clicks in the presence of high background noise. For instance, the peak frequency of bimodal clicks appears to be slightly lower than the peak frequency of single-peak clicks. The background noise in this study displayed higher amplitudes as frequencies fall below 20kHz, but lower amplitudes at frequencies progressed beyond that point. Therefore, shifting peak frequency to lower bands does not seem beneficial, unless some sort of high frequency component is also present. Not surprisingly, bimodal clicks were produced more often as background amplitude increased within the 15-25kHz bandwidth, indicating the that their second most significant frequency, which was always higher in frequency, may used under such conditions.

Though the relationship between peak frequency shift and background noise is not significant, the potential for it to happen still remains. It is possible that the variance in background noise in this study was not sufficient to warrant a frequency shift to higher, less interfering frequencies. It would be helpful to do a similar study comparing clicks recorded during summer and winter months. Presumably, the waters that these whales inhabit during the winter months would be much quieter insofar as less, if any, boats would be present. Clicks harvested from these waters would likely provide the variance in background noise needed to adequately answer the question posed in this paper.

Still, it would seem as though Southern Resident killer whales are making an effort to present high frequency components in their clicks in the midst of loud waters. Though they do not appear to be shifting their peak frequencies higher, they are at least devoting some energy to areas of the frequency spectrum that encounter less interference, and doing it more often when their go-to frequency meets interference. What's more, the average frequency of the *f*p2 in bimodal clicks was 38922.2Hz, a frequency that a killer whale is only slightly less sensitive to than its most sensitive frequency pending the validity of the audiogram given in this paper. While only the background noise within the 15-25kHz was analyzed, amplitude levels in exceeding frequencies were, at least visually, consistently lower. If that is indeed the case, then the average *f*p2 is positioned at a point in the spectrum that meets less interference. However, because the source levels of these clicks were not found, it is not known if enough power is generated at that second peak to be of any use (i.e. there is still possibility that they may be masked by the background noise). In any case, further research is needed to verify these findings as this study investigated only a small handful of the clicks that may represent only a few individuals.

While it would be irresponsible to extrapolate general information about clicks from one individual, it is important nevertheless to note that all J-1 clicks were bimodal, which hints at some important ideas. Male killer whales dive to great depths more often than females and juveniles presumably because their bodies are larger and thus contain more oxygenated blood ref?. This presumably broadens the scope of potential prey items for males. The average peak frequency of killer whale echolocation clicks is specially suited to seek out the swim bladders of Chinook salmon. If that peak frequency is masked by background noise, and with the presumed extensiveness of prey items for males, it may be beneficial for them to utilize different frequencies that may be suitable for finding prey other than Chinook. Again, a much larger sample size would be required for any definite conclusions to be made.

ACKNOWLEDGMENTS

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