Killer Whale (*Orcinus orca*) echolocation click rates during various behavioral states and ambient noise levels

Hana Kazunas
Beam Reach Marine Science and Sustainability School
Friday Harbor Laboratories
620 University Road, Friday Harbor, WA 98250
kazunash@carleton.edu

Abstract

Echolocation is an important tool for navigation and detecting prey used by the recently endangered Southern Resident killer whales (*Orcinus orca*) of the Salish Sea. Many studies have been performed on echolocation, but the exact manner in which echolocation clicks are used has yet to be determined. This study used acoustic recordings to look at average click rates per minute in respect to ambient noise levels (dB), hypothesizing that click rates would increase as ambient noise levels increased. However, no statistical significance was found. This study also compared click rates/min. in respect to behavior states, and found statistical differences across behaviors, specifically between foraging and resting ($p = 0.0005$), and resting and socializing ($p = 0.0382$) and traveling ($p = 0.0407$). Though additional studies are needed for more concrete conclusions, this study shows preliminary trends in echolocation use in respect to ambient noise levels and behavior states. More statistical significance that suggests stronger conclusions may be able to be used to create guidelines or shelter critical areas and therefore better protect the Southern Resident killer whales.

Key words: *Orcinus orca,* killer whale, echolocation click rate, behavior states, ambient noise

Introduction

The largest member of the family Delphinidae, killer whales (*Orcinus orca*) are fearsome predators who are highly social with complex family structures. In the waters off British Columbia and Washington State alone, two resident orca communities live, and many smaller transient orca populations frequent the waters (Bigg et al. 1987). Residents and transient ecotypes differ significantly, especially when it comes to foraging. Residents, made up of the Northern and Southern communities, are fish-eaters, using echolocation clicks frequently during foraging behavior, while transients are marine mammal-eaters who typically remain quiet and use stealth to catch their prey (Bigg et al. 1987).

In November of 2005, the Southern Resident killer whale (SRKW) population was listed as an endangered species under the Endangered Species Act of 1973. Because of this, extra precautions are being set in place in order to protect this species from declining further. In 2008, the National Marine Fisheries Service (NMFS) created a recovery plan to help promote the well-being of the SRKWs. Although it is difficult to know which threat or combination of threats cause the most harm, the whales' biggest dangers are inadequate nutrition, chronic stress (including the stress of vessel impacts and toxin buildup), and ultimately, a decline in an already small population (NMFS 2008).

Ford et al. (1998) determined resident killer whales' prey of choice was the Chinook salmon, likely due to its large size and high lipid content. However, research from the Recovery Plan (NMFS 2008) notes that salmon populations of all species are in decline, due to exploitation by humans, loss of habitats, and increased contaminants in the environment. With salmon, especially Chinook salmon, as the SRKW's main prey source, a decline in salmon abundance means less prey for the whales. Inadequate nutrition makes it harder for the whales to maintain homeostasis, which can lead to increased stress levels.

The stress of being a little hungry might not ordinarily affect the overall health of a whale, but there are many other additional stressors that factor into the SRKW's lives today. The presence of large numbers of vessels like ferries, whale-watching boats, large ships, and privately owned boats not only add obstacles that the whales must avoid, but contribute a considerable amount of noise to the ambient sound levels. This has the potential to mask echolocation clicks and cause temporary or even permanent hearing loss (NMFS 2008). Veirs and Veirs (2005) found that short-term sound pressure levels (SPL dB re 1 µPa) in Haro Strait varied from ~95-130 dB, while the long-term average was ~115 dB. However, large ships moving through the area can temporarily raise the SPL ~20-25dB and even smaller boats can elevate short term SPL ~15-20dB—a significant difference from an SPL of ~95dB found without the presence of vessels (Veirs and Veirs 2005). Whales were found to increase their acoustic source levels by 1 dB for every dB that the ambient noise level was raised (Holt et al. 2009). If whales are forced to work harder to find an already diminished prey population, stress levels could elevate significantly (NMFS 2008). Possible examples for increased effort by the whales include increasing the amplitudes of vocalizations, varying their path due to vessel obstruction, and foraging longer due to echolocation click masking by increased background noise.

The SRKWs are divided into three subpods: J, K, and L (Bigg et al. 1987). Killer whales have a matrilineal society, and resident orcas usually stay in their mothers' pod for their entire lives. Orcas communicate using both echolocation and calls. Echolocation is thought to help the whales navigate and find prey while foraging; echolocation clicks are directional sounds with a high amplitude, broadband frequency structure, and short duration (Bigg et al. 1987 and Ford

1989). In addition, Au et al. (2004) determined that orca echolocation clicks have a center frequency of 50 kHz and source levels ranging from 195 to 224 dB *re*: 1 µPa.

Whales receive an echo of the click they produce after it bounces off an object, which is how they gain information about both prey and their surroundings. The amplitude of the echo depends on many factors, two of which are ambient noise level and target strength. Click rate depends on the length of time it takes for the click to bounce off a target and the echo to return to the whale. Upon receiving an echo, whales may then produce another click for that target. Killer whales' most sensitive hearing frequencies range from 18-42 kHz, and Erbe (2002) modeled that ambient noise levels can be loud enough to mask echolocation clicks a certain distance away from a target (Szymanski et al., 1999). When this occurs, whales will have to be closer to their target before they are able to hear the echo that returns to them. Because of this smaller distance between source and target, the click rate would increase because less time will pass before the echo returns to the whale.

Au et al. (2004) modeled foraging of echolocating odontocetes, estimating that resident killer whales would be able to detect a 0.78 m long Chinook salmon from about 100 m away in relatively calm and quiet waters. Detection distance might be greater but researchers did not know if killer whales would approach a fish from farther than 100 m (Au et al. 2004). Although echolocation has been studied for many years, the exact way whales use it while foraging, or how they determine one species of fish from another is still being studied. Houser, D.S., Helweg, D.A., and Moore, P.W. (1999) characterized seven click types in Atlantic bottlenose dolphins, and found that usage of click types varied between individual dolphins and tasks. Different click types (i.e. differences in frequency, rate, and amplitude) are used by the animals to determine different information, but more studies need to be performed in order to determine which clicks will be used, and when.

SRKWs generally move as a pod, although sometimes smaller groups, typically made up of one mother and her offspring, will separate and forage alone. Most individual whales in a resident pod tend to have the same overall behavioral state (moving in the same direction and engaging in similar general activities) as the rest of the pod (Hoelzel 1993). It can be hard to classify behavior states because of the spread of a pod of whales, and one of the biggest problems researchers face is defining behavioral states based on surface observations alone.

Whales use echolocation in daily living, navigating, and detecting prey while foraging, though exactly how echolocation is applied in their natural environment has yet to be determined (Au et al. 2004). Click use is spread across all behavior states and knowing how echolocation applies to the different behavior states would help researchers protect critical habitats, especially those that are used extensively for foraging. SRKWs are fighting an uphill battle for their species to carry on, and need positive change to survive.

This experiment explored two questions. Both questions look at echolocation click rates used by SRKWs. These questions were posed in hopes of providing conclusions that could help further protect the killer whales of the Salish Sea.

Because of the increasing number of noise-producing vessels around the SRKWs, the first question looked at the relationship between click rate and background noise level. It tested the hypothesis that as background noise increases so will click rate, because during loud conditions, an orca must be closer to its target in order to hear an echo. This results in a faster click rate. If there is a significant difference in click rate for different levels of background noise, it can help researchers determine if increasing vessel numbers, background noise levels, or both, affect the whales the most, and will allow managers to set guidelines for permissible vessel numbers and/or noise levels in the vicinity of the whales. As increased ambient noise levels cause whales to click more often, it could raise stress levels, and this additional energetic cost could cause enough stress to weaken whales to the point of sickness and even death. If researchers knew set values of increased click rate, they could use this information to better quantify the effects of ambient noise on the whales, and guidelines could be set in place in order to protect the whales.

The second question compared click rate to behavior states. It tested the hypothesis that echolocation click rates will be highest during foraging and traveling. There is no clear answer about when orcas use echolocation the most. It is thought that the whales use it for navigation and prey detection, making traveling and foraging behavior states more likely to have a higher click rate. Behavior is difficult to categorize based on surface activity alone, and if click rates could be used to determine what behavior state whales were in, researchers could have more insight into the whales' lifestyle. For example, if researchers had more knowledge about when whales were socializing, it might be possible to learn more about social acts, like playing and mating. In addition, more information about when and where whales forage could allow researchers to protect critical feeding grounds, allowing the whales to have more access to food. The more information about the whales' lifestyles researchers have, the better equipped they are to protect the whales.

Methods

Data Collection

Data was collected by observing the whales in their natural habitat in the Salish Sea from September 13th until October 23rd. Observations were made from the deck of the *Gato Verde*, a 42' long sailing catamaran. The behavior states used were the same as those described in the 2004 National Oceanographic Atmospheric Administration (NOAA) SRKW workshop: resting, traveling, foraging, socializing, and milling. Resting is defined by close contact (flank or nonlinear formation), slow but directional movement, high breathing synchronization and very few clicks or calls. Traveling is characterized by directional movement, with the whales swimming at any speed at relatively close distances to one another. Foraging behavior is extremely difficult to characterize—essentially any orientation, spread distance, direction, and speed can be seen. Barrett-Lennard et al. defined foraging behavior of residents by "erratic high-speed swimming, lunging, rapid circling and chasing fish at the surface" (Barrett-Lennard et al. 1996, p. 555). The SRKWs often vocalize frequently while foraging, using clicks especially often. Because of this, researchers also tend to use acoustic data to determine when orcas are foraging. Socializing behavior includes three categories: object play, social interactive play, and solitary play. There are no parameters for pod formation, speed, or directionality during play, but socializing can include events such as kelping, touching, breaching, and percussive behaviors (like tail and pectoral fin slaps). Milling is characterized as a nonlinear orientation where the whales are spread any distance and moving at a slow or medium pace (NOAA 2004). More detailed descriptions of behavior can be found in the 2004 SRKW Behavior Workshop and the 1996 Barret-Lennard et al. paper (NOAA 2004, Barrett-Lennard et al. 1996).

The following data was recorded: time, behavior state of the whales, whale orientation to the boat, pod size, and any notes about that time period. Data collection began at the same time as the hydrophone recording began. The time, the date, and a GPS waypoint were documented when the recording started and finished. Time was recorded at five minute intervals, unless the behavior state or the orientation of the whales changed, in which case the time, new orientation and behavior were noted. The whales' orientation to the boat was compared to a clock face with 12 o'clock at the bow and the clock orientation continuing clockwise around the boat; see Figure 1 in the appendix for more details. The number of whales present at each clock orientation was counted, and the calculated click rate was divided by the number of whales present in order to control for varying group sizes. The overall behavior state was assumed to be the same in all smaller groups because activities tend to be the same for all members of the pod, even if the groups are spread out in different orientations to the boat (Hoelzel 1993). Pertinent Washington State laws and Be Whale Wise guidelines were followed in order to protect the whales and reduce observer error.

A Labcore four hydrophone array and a single Cetacean Research Technology C54 XRS/266 (CRT) high-frequency hydrophone were towed behind the *Gato Verde*. This study required only the use of the CRT which has a flat response curve from 1 to 30 kHz. The CRT was attached to the boat on a line 28.05 meters long and weighted to a depth of 1.85 meters. Continuous acoustic recordings were done by two, two channel Sound Devices 702 recording units. However, the CRT hydrophone uses only one channel, recording digitally at a sampling rate of 192 kHz and a 16 bit depth rate. The gain settings on the Sound Devices were set at 37.3 and the CRT was calibrated at this setting using a Interocean Systems Model 902 hydrophone calibration system.

Data analysis

Data analysis was done on a Sony VAIO computer, model VGN-C290, using the programs Audacity 1.3 Beta (Unicode) and Raven Lite 1.0. Acoustic recordings were split into minute-long WAV files in order to analyze click rate per minute easily. Recordings were listened to and looked at using both time series and spectrograms (figure 1). In addition to counting individual clicks, the number of click trains, defined in this study as successive clicks with 0.05 seconds or less between each click, was counted in each WAV file.

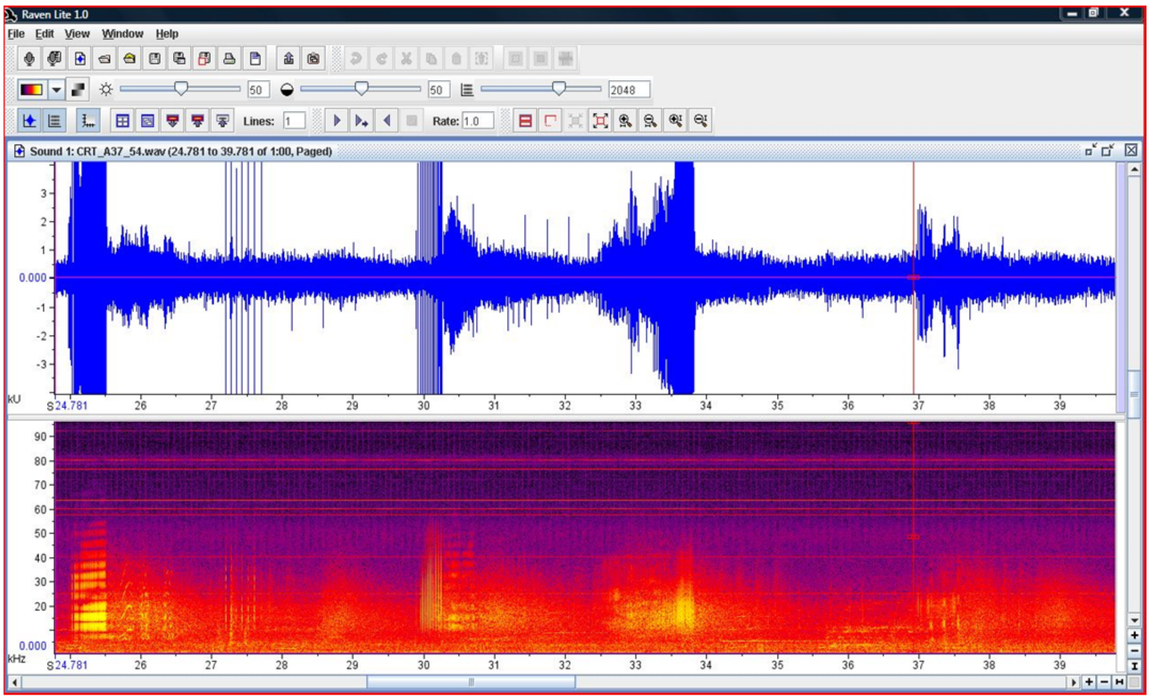

Figure 1. Screenshot of the program Raven Lite 1.0, used to analyze data. This screen shows a segment of a WAV file, in both time series (top) and spectrogram (bottom). The x-axis is time in seconds and the y-axis is frequency in kHz. The FFT used was 2048 and the color mode was "hot," with brighter colors representing louder amplitude. An example of a click train can be seen on the far left side of the screenshot at 25 seconds, followed closely by a call at 26 seconds, and with individual clicks between 27 and 28 seconds. More individual clicks and click trains are seen later in the sample.

Clicks were counted using a custom designed program, the Beam Reach Analyzer, created by Val Veirs. Before using the program to analyze large quantities of data, it was correlated with a sample of minutes that were hand-counted in order to ensure that the program was counting clicks accurately (figure 2). There was a strong, positive correlation, which validated program use in data analysis. An averaging window of 90 microseconds, just longer than a typical echolocation click, was used. The analyzer searched for peaks of amplitude by running this averaging window across the absolute value of the data for each data point in the minute-long WAV files. As scans progressed, each time the averaging window reached a peak, the sample number and amplitude (mV) of the highest peak within the 90 microsecond window were recorded as a histogram of the number of peaks versus the amplitude of each peak. These reports were transferred into an Excel worksheet for further analysis. In order to get the most accurate click rate, a low amplitude threshold was determined for each file by looking at the data in Raven Lite 1.0 and Audacity 1.3 Beta (Unicode) and determining which peak was the minimum amplitude while still being seen and heard. The determined amplitude was cross-correlated with the analyzer output, and only peaks at amplitudes higher than the threshold were counted. However, if the signal-to-noise ratio (SNR) was low, individual clicks were counted by hand in order to maintain accuracy.

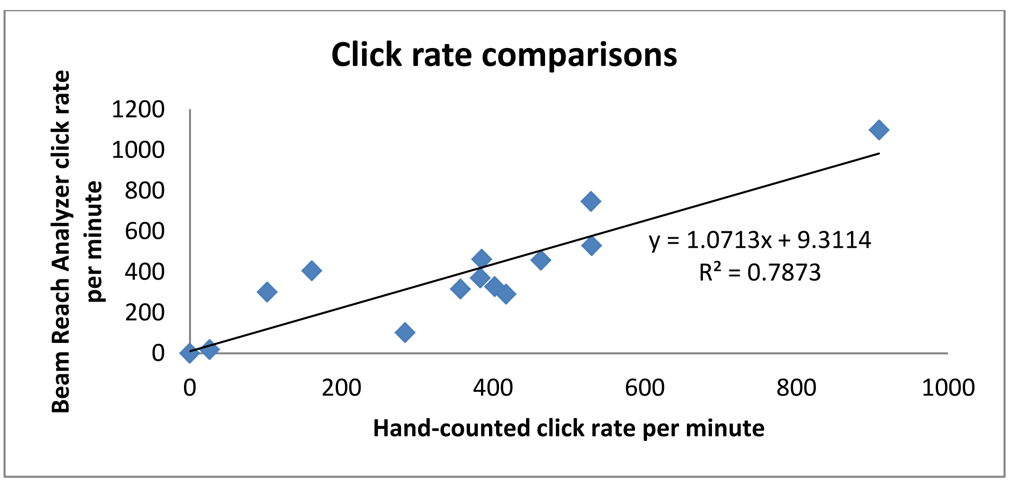

Figure 2. Click rate comparisons. A comparison of click rate determined using the Beam Reach Analyzer and click rates counted by hand.

The recordings were initially sorted by the orientation of the whales. Any minutes where whales were located between 10 o'clock and 2 o'clock were discarded because echolocation clicks are directional, and it would be extremely difficult to detect clicks and calculate an accurate click rate generated by whales in that location. The final counted (by hand or by the Beam Reach Analyzer) click rate was divided by the number of whales present at the time of data collection. This controlled click rate was compared to background noise levels, measured one time from each minute-long WAV file in Audacity. A calibration factor of 159 was added to Audacity dB for accurate amplitude readings. The controlled click rate was compared to behavior states as well.

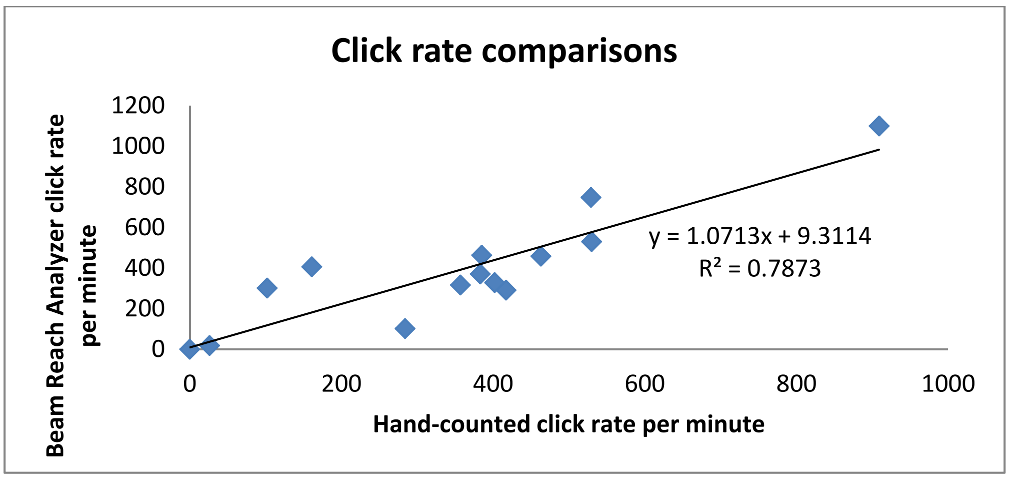

Figure 2. Click rate comparisons. A comparison of click rate determined using the Beam Reach Analyzer and click rates counted by hand.

Results

Acoustic recordings were made over nine different days. Recordings were still taken even if no vocalizations could be heard, and some of those minutes were included in analysis in order to determine the most accurate click rates. This study analyzed 154 minutes of data taken from seven separate days.

Ambient noise levels

There was no significant difference in click rate as ambient noise levels increased (figure 3). A linear regression was performed on the data, however there was very little correlation between click rate and ambient noise levels ($R^2 = 0.0388$). These results do not support the hypothesis stated.

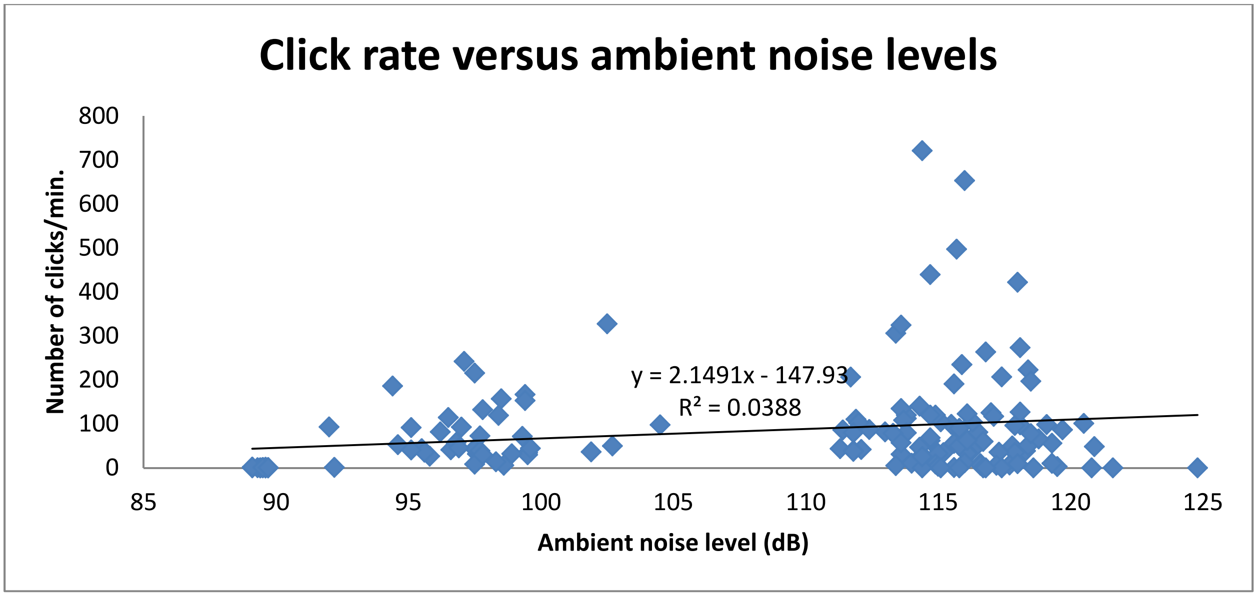

Figure 3. Click rate versus ambient noise levels. There are two major clusters of data points; the cluster of data points at the lower ambient noise levels is predominately from one day of data collection. However, no significant trend is seen even if that data is not included.

Click rates during specific behavior states vs. ambient noise levels were also graphed, but there was no statistical significance seen in that analysis either (figures 2 through 6 in the appendix show the individual graphs). However, it was noted that there appears to be a certain threshold at which either whales stop producing echolocation clicks or the clicks being produced are unable to be heard (figure 4). For most behavior states, clicks were no longer detected at an ambient noise level between 117.1 and 118.8 dB, however the last click detected during foraging occurred at 120.9 dB—two dBs louder than the other behavior states. This preliminary analysis suggests an interesting trend in click detection in respect to ambient noise levels.

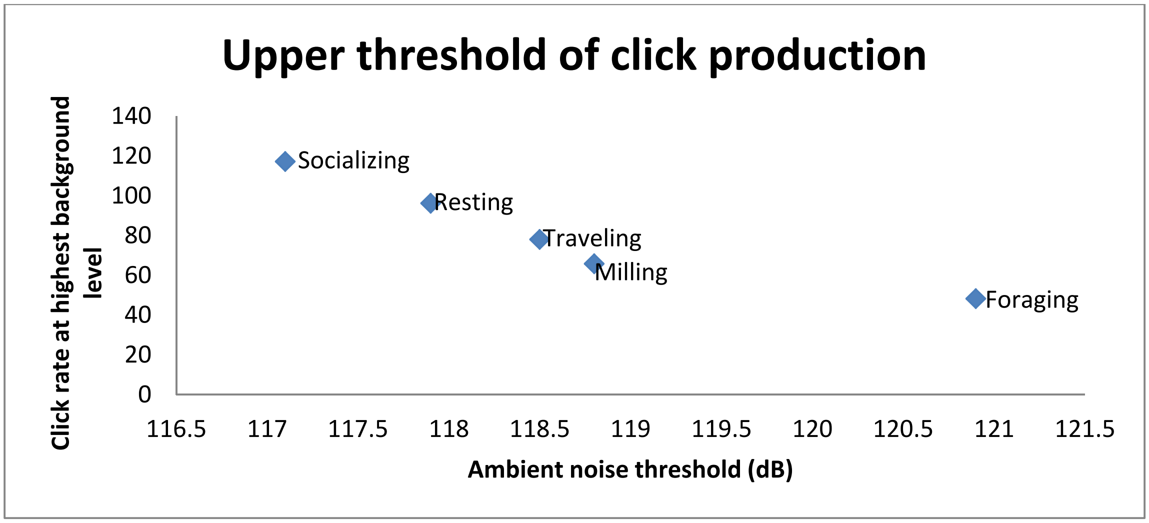

Figure 4. Upper threshold of click production. This graph shows the click rate of the minute that had the loudest ambient noise level (dB) for each behavior state. Clicks while foraging were detected at the loudest ambient background level.

Behavior States

Of the 154 minutes of data analyzed, 54 minutes were foraging, 22 minutes were milling, 23 minutes were resting, 5 minutes were socializing, and 52 minutes were traveling. When possible, behavior states were taken from samples recorded on at least two separate days in attempts to get an accurate representation of the SRKWs. Socializing was a rare behavior to see while recording, and the five minutes analyzed in this study were the only samples available. Socializing had the highest average click rate of 180.0 clicks/minute. Traveling had the next highest rate of 118.6 clicks/min., followed by foraging with a click rate of 79.8 clicks/min. Milling and resting had the lowest rates of 48.1 clicks/min. and 46.0 clicks/min, respectively (figure 5). In order to pass the Shapiro-Wilk normality test and meet the assumptions of a one-way ANOVA (and therefore determine if trends seen were statistically significant), the data was fourth square root transformed, and statistical significance was found across behavior states ($F_{4,153}$=5.05, $p = 0.001$). Because there was significance across behavior states, a Tukey pairwise multiple comparison test was performed to determine which specific behavior states had significant differences between them. Foraging was statistically different from resting (T = -4.147, p = 0.0005). Resting was also significantly different from socializing (T = 2.862, p = 0.0382) and traveling (T = 2.838, p = 0.0407). Statistical significance supported elements of the hypothesis and there are additional noteworthy trends.

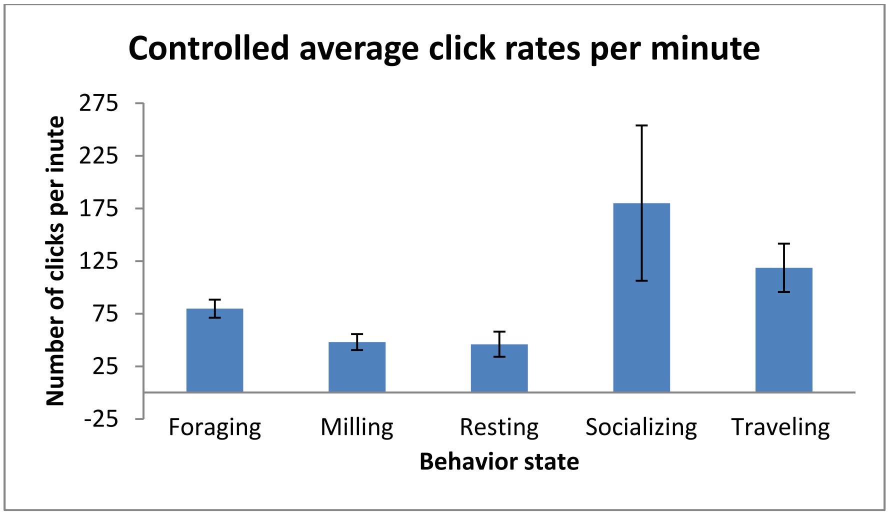

Figure 5. Controlled average click rates per minute. All values given are averages of click rate/min. for various behavior states ± standard error of the mean.

In addition to average click rates, the controlled (for number of whales present) average number of click trains in the minute-long samples (train rate) were compared to behavior states. Traveling had the highest average number of click trains per minute at 0.80 trains per minute, followed by socializing with 0.75 trains per minute, foraging with 0.71 trains per minute, milling with 0.39 trains per minute, and resting with the lowest average of 0.14 click trains per minute (figure 6). The raw data failed the Shapiro-Wilk normality test, and was unable to be transformed to pass the normality test, so a Kruskal-Wallis ANOVA was performed and found significance across behavior states (N = 154, H_4 = 18.335, p = 0.001). To determine which behavior states had significance between each other, a pairwise multiple comparison (Dunn's method) was performed and significance was found between foraging and resting (Q = 4.030, p = <0.05).

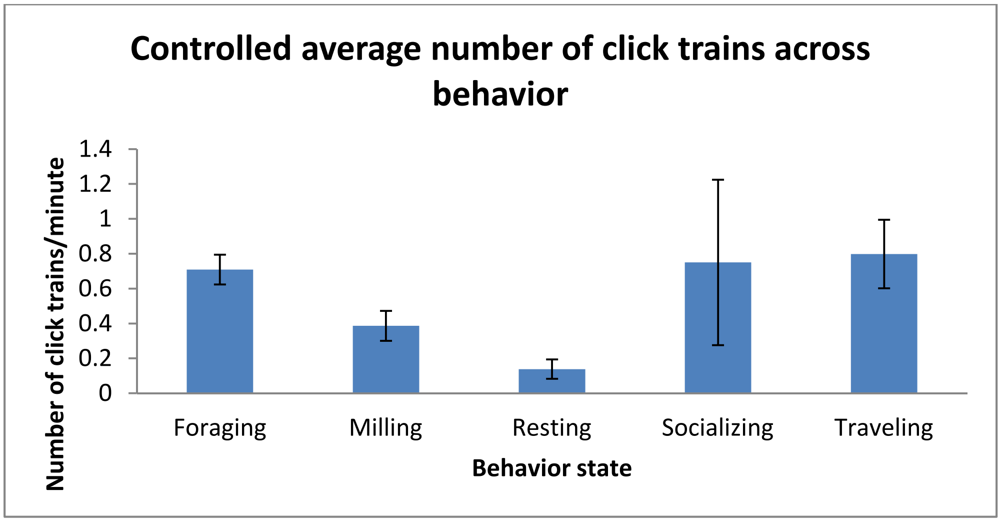

Figure 6. Average number of click trains across behavior states. All values shown are averages of the number of click trains per minute (train rate) for various behavior states ± standard error of the mean.

Discussion

The hypotheses given were not wholly supported, but aspects were supported with statistical significance. In addition, many noteworthy trends were seen that may help develop further studies.

Ambient noise levels

Click rates did not increase as ambient noise levels increased as originally hypothesized. There was no apparent correlation between ambient noise level and click rate. This may be due to an inherent difficulty in testing this hypothesis: as background noise levels increase, it becomes more and more difficult to hear clicks produced by whales. In addition to possible masking, as ambient noise levels increase, the SNR is often low, making it difficult to obtain accurate click rates. If masking is occurring and whales are forced to click at a higher rate in order to receive feedback, the clicks that are masked may not be able to be detected by recording devices. If this is the case, more accurate studies could be performed by placing recording devices closer to the whales, or using acoustic tags, assuming they could pick up the directional clicks. Holt et al. (2009) found whales to raise vocalizations 1 dB for every dB increase in ambient noise, and this may be a more appropriate explanation for how whales handle an increase in ambient noise—they don't click more often, they click louder.

Although the hypothesis surrounding ambient noise was not supported, it was interesting to see a preliminary suggestion that there may be a threshold at which whales stop producing echolocation clicks at all. Although more data is needed before making conclusions about this hypothesis, it is interesting to note that foraging was the behavior state that had the highest threshold for click production. One hypothesis is that the other behavior states do not rely on echolocation as much as foraging for success, and it is worth the extra energetic cost to produce louder clicks in order to locate prey. It would be an interesting study to explore a threshold at which it becomes too energetically expensive to continue to produce echolocation clicks. Once again, acoustic tagging, or closer proximity to the whales may be necessary in order to determine when whales stop producing clicks, and when the clicks can simply not be picked up by acoustic recording devices.

Behavior States

The hypothesis that foraging and traveling would have the highest click rates was not wholly supported by the results from this study; however, there were trends that were notable. Traveling had the second highest click rate of all behavior states, which supports the hypothesis.

Socializing had the highest click rate, which agreed with the results found by Erica Beneze (2009), a previous Beam Reach student who also studied click rates in various behaviors. Although Beneze did not control for the number of whales at the time of data collection, she found playing (equivalent to socializing in this study) to have the highest click rate, followed by foraging, traveling, milling, and finally resting; milling and resting having the lowest click rate also agrees with the results of this study (2009). The results from this study do not agree with the 1996 Barrett-Lennard et al. study that found foraging to have the highest click rate across behaviors.

Though foraging was hypothesized to have one of the highest click rates, it is possible that accurate representations of clicks were not obtained due to the high amount of sporadic movement and lunging that occurs during foraging. When whales are in other behaviors states such as resting or traveling, they are typically directional, making it easier to position the research vessel in an orientation that is able to detect the directional clicks. When whales forage, they may be turning away from the hydrophones while pursuing prey, which would give an inaccurate click rate.

Additionally, Ridgway, S. H. and Carder, D. A. (1997) found a deaf/mute bottlenose dolphin who was never heard to produce a call or echolocation click, yet was able to forage and maintain a healthy body weight. The dolphin clearly used other mechanisms besides echolocation to forage, and it’s possible that these strategies are inherent in all cetaceans. The whales from this study may have been using other hunting techniques, like visual or auditory cues, and didn’t rely on echolocation as much as hypothesized.

By definition, socializing includes interactions between whales, and it is possible that the high click rate seen in this study demonstrated a communicative property of echolocation clicks.

However, the sample size for socializing behavior was also very small, and this could be a source of error and an inaccurate representation of click rate while socializing (it was not significantly different from any other behavior state). Milling and resting had the lowest click rates of all the behavior states. This agrees with idea that echolocation is most used for detecting prey and aiding in navigation (Bigg et al. 1987 and Ford 1989).

The preliminary results found for controlled average number of click trains per minute displayed a trend almost mirroring the trend seen in controlled average click rate per minute; the only difference was that traveling had the highest controlled train rate, with socializing having the second highest train rate. This makes sense as the clicks in click trains are accounted for when counting the overall controlled click rate per minute. One hypothesis is that click trains may help with navigation; as a whale detects an object or solid surface in the water, it zones in on its target, and as it gets closer the rate increases into a click train. The same hypothesis could be applied to click trains in foraging behavior. Resting and milling have the lowest train rates, respectively, and also follow that hypothesis; if echolocation is used predominately for prey detection and navigation, there would be no need for trains during behavior states that did not include these activities. This hypothesis does not explain why socialization had such a high click rate, unless click trains also have some sort of communicative property. However, the small sample size of socializing behavior may explain why this data had such a high click train rate.

Another hypothesis could be that click trains represent something different altogether than individual clicks, such as warnings or some other sort of acoustic signal. Only additional studies could suggest what this meaning might be. Though more studies need to be done in order to draw significant conclusions about average click train rates across behavior states, it is an interesting prospect that could prove useful in determining behavior states based on acoustical cues alone. If click train rates differ significantly across behavior states, it is one more tool researchers could use to protect the whales.

Sources of Error

Field studies provide many challenges for researchers. Weather and study subjects often don’t cooperate, especially when the subject spends the vast majority of its time underwater. Defining and correctly identifying behavior states based on surface activity alone is challenging at best. Resting behavior can blur with slow travel, which can be confused for milling. Foraging often takes place underwater. Behavior observations were made by one person in order to reduce observer error, but it is possible that behavior states were incorrectly identified. Although this study tried to control for whale orientation to the boat, there were moments included where one or more whales were not positioned in a manner that allowed the boat hydrophones to detect clicks, giving an inaccurate click rate. In addition, the number of whales present was recorded, but when large groups of whales were swimming together it was difficult to count the exact number, which could cause error in the controlled average click rates.

There is the possibility for error during data analysis as well as during data collection. For example, the Beam Reach Analyzer used to count peaks may have counted peaks that were due to non-whale sources, or under/over-counted peaks for some minutes, causing a slightly inaccurate calculated click rate. In addition, there could have been human error when determining the lowest amplitude threshold of clicks in each WAV file.

Future Research

Many future studies can be made from results found in this paper. It would be interesting to continue studying click rates in respect to ambient noise, by either getting permits to get closer to the whales in hope of detecting clicks that might be masked from farther distances, or by using acoustic tags at the source of the clicks. In addition, it would be interesting to see if there really is a threshold at which it becomes too energetically costly to use echolocation, and if so, if that threshold varies based on behavior state.

Many further behavior studies could be done. It would be interesting to simply repeat this study to see if more minutes of analyzed data would affect the end conclusions. Data could also be collected at night, where ambient light is significantly lower, and determine if click rates vary based on light availability. This could help decide if, and when, other foraging techniques are being utilized. It would also be interesting to attempt to follow the SRKWs in different seasons, especially winter, when the whales go out to an open ocean habitat, to see if different habitats, including those that may have less vessel traffic than the Salish Sea, invoke different click rates. Finally, more studies on the use of click trains compared to individual clicks in respect to behavior states could be done to determine if single clicks are used for different purposes than click trains.

Concluding Statement

Although significant results were found, overall conclusions would benefit from a larger data set. However, the data do suggest that:

- Increased ambient noise levels pose threats to the endangered SRKWs as it may compromise the whales' ability to use echolocation effectively.

- More significant results would allow managers to set guidelines on vessel numbers or ambient noise levels in the vicinity of the whales, potentially protecting the overall health of the whales.
- More conclusive results about click rates during various behavior states could allow researchers to protect critical habitats to the whales.

This study provides a good preliminary basis on which to build, and potentially establish accurate guidelines about overall whale health.

Acknowledgements

I would like to give utmost thanks to Dr. Jason Wood for his continuing guidance, ever-open office door, and humor throughout this process. I thank Dr. Val Veirs for his wonderful computer program writing skills and ability to pick up on ideas I might have otherwise overlooked. I'd like to thank to Dr. Scott Veirs for his help organizing not only the logistics of the Beam Reach program, but also the scrambled thoughts in my head. A special thanks goes to Capitan Todd Shuster for not only keeping me safe on the water, but showing me the art of sailing and navigation. Thanks especially to my fellow Beam Reach peers—Catherine Peters, Garrett Turner, Megan Stoltzfus, Dave Cade, and Vanessa Victoria for helping with not just data collection but making this experience not only educational, but fun and entertaining as well. To everyone who helped us find the whales, a much appreciated thanks goes out to you! And finally, thanks to all my friends and family for their continuous support (and care packages!) throughout this entire experience.

References

Au, W. W. L., Ford, J. K. B., Horne, J. K., and Allman, K. A. N. 2004. Echolocation signals of free-ranging killer whales (*Orcinus orca*) and modeling of foraging for chinook salmon (Oncorhynchus tshawytscha). Journal of the Acoustical Society of America 115:901-909.

Barrett-Lennard, L. G., Ford, J. K. B., and Heise, K. A. 1996. The mixed blessing of echolocation: Differences in sonar use by fish-eating and mammal-eating killer whales. Animal Behaviour 51:553-565.

Beneze, Erica. Echolocation use by southern resident killer whales (*Orcinus orca*) while foraging. Beam Reach Marine Science and Sustainability School. http://www.beamreach.org/091dir/final-paper-erica-beneze.pdf. 28 October 2010.

Bigg, M. A., Ellis, G. M., Ford, J. K. B., and Balcomb, K. C. 1987. Killer Whales: a study of their identification, genealogy and natural history in British Columbia and Washington State. Phantom Press, Nanaimo, B.C.

Erbe, Christine. 2002. Underwater noise of whale-watching boats and potential effects on killer whales (*Orcinus orca*), based on an acoustic impact model. Marine Mammal Science 18:394-418.

Ford, J. K. B. 1989. Acoustic behaviour of resident killer whales (*Orcinus orca*) off Vancouver Island, British-Columbia. Canadian Journal of Zoology 67:727-745.

Ford, J. K. B., Ellis, G. M., Barrett-Lennard, L. G., Morton, A. B., Palm, R. S., and Balcomb, K. C. 1998. Dietary specialization in two sympatric populations of killer whales (Orcinus orca) in coastal British Columbia and adjacent waters. Canadian Journal of Zoology 76:1456-1471.

Hoelzel, A. R. 1993. Foraging behaviour and social group dynamics in Puget Sound Killer Whales. Animal Behaviour 45:581-591.

Holt, M. M., Noren, D. P., Veirs, V., Emmons, C. K., and Veirs, S. 2009. Speaking up: Killer whales (*Orcinus orca*) increase their call amplitude in response to vessel noise. Journal of the Acoustical Society of America 125:27-32.

Houser, D.S., Helweg, D.A., and Moore, P.W. 1999. Classification of dolphin echolocation clicks by energy and frequency distributions. Journal of the Acoustical Society of America 106:1579-1585.

National Marine Fisheries Service. 2008. Recovery Plan for Southern Resident Killer Whales (*Orcinus orca*). National Marine Fisheries Service, Northwest Region, Seattle, Washington.

National Oceanographic Atmospheric Administration. 2004. Southern Resident Killer Whale Behavior Workshop. NOAA NMFS Northwest Fisheries Science Center. Seattle, Washington.

Ridgway, S. H. and Carder, D. A. 1997. Hearing deficits measured in some *Tursiops truncatus*, and discovery of a deaf/mute dolphin. Journal of the Acoustical Society of America 101:590-594.

Szymanski, M. D., et al. 1999. Killer whale (*Orcinus orca*) hearing: Auditory brainstem response and behavioral audiograms. Journal of the Acoustical Society of America 106:1134-1141.

Veirs, V., and Veirs, S. 2005. Average levels and power spectra of ambient sound in the habitat of Southern Resident orcas. Report to NOAA/NMFS/NWFSC. Web. http://www.coloradocollege.edu/dept/ev/research/faculty/OVALitems/pdf_Papers/051204noaa-haro_noise_final.pdf . 1 September 2010

Appendix

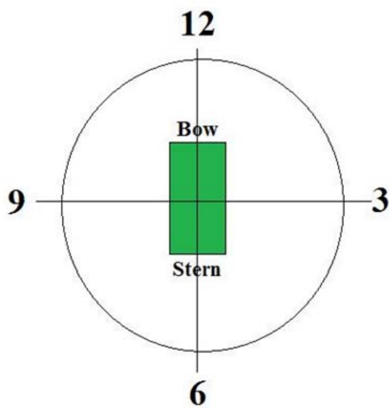

Figure 1. Clock orientation of whales in reference to the *Gato Verde*.

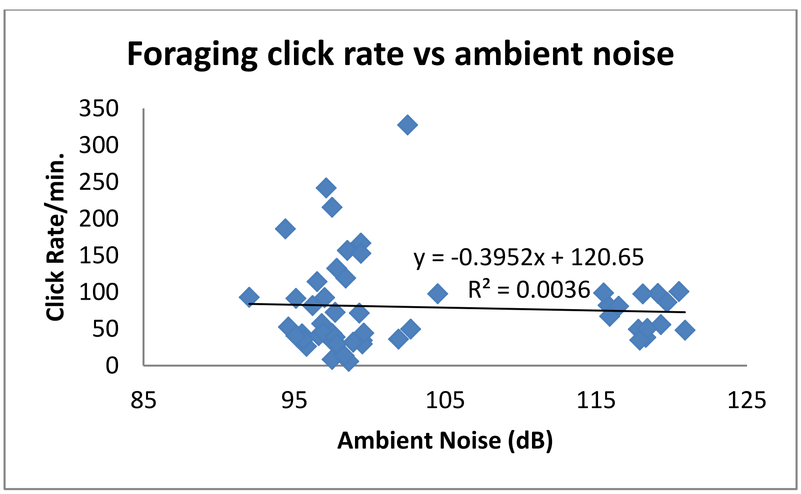

Figure 2. Foraging click rate vs. ambient noise. Click rates shown were taken only while whales were foraging.

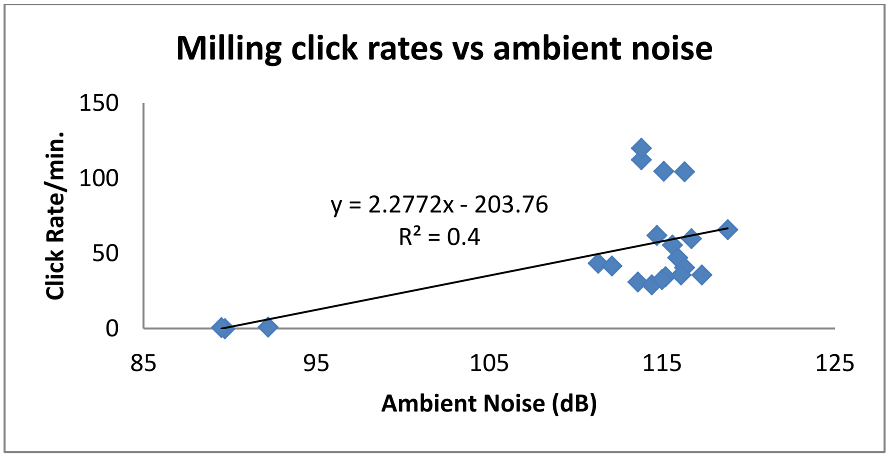

Figure 3. Milling click rates vs. ambient noise. Click rates shown were taken only while whales were milling.

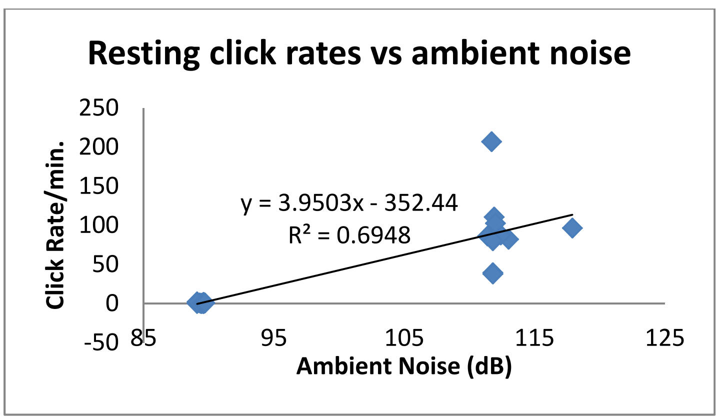

Figure 4. Resting click rates vs. ambient noise. Click rates shown were taken only while whales were resting.

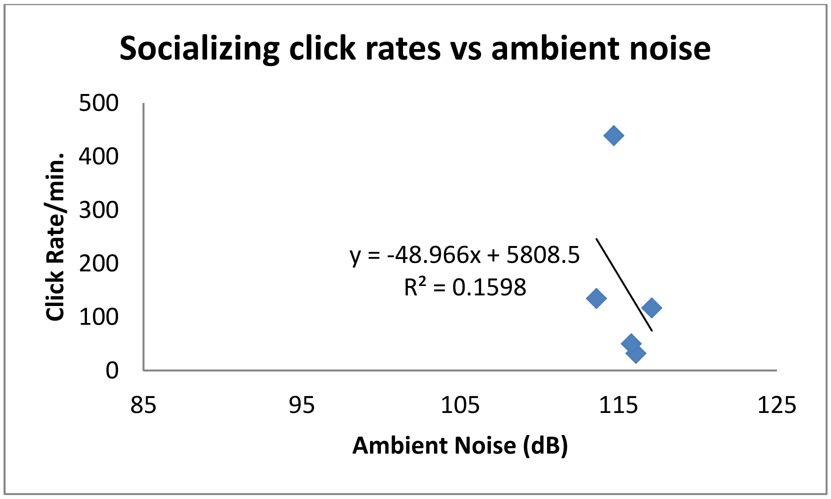

Figure 5. Socializing click rates vs. ambient noise. Click rates shown were taken only while whales were resting.

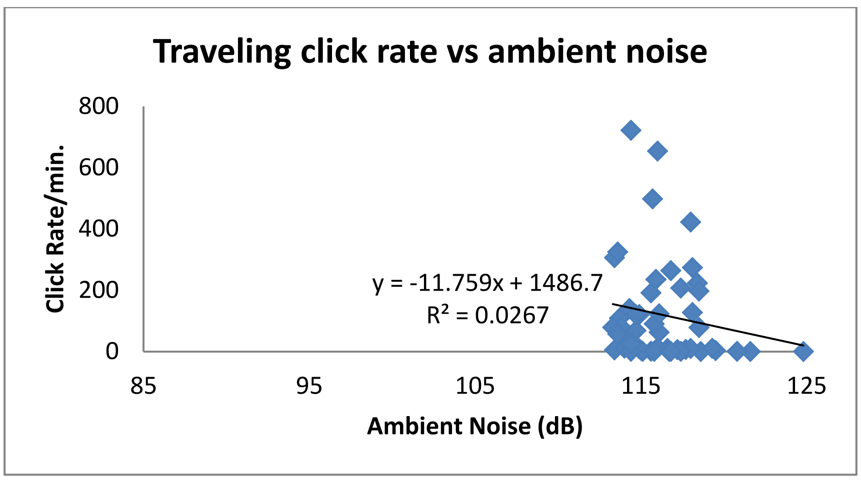

Figure 6. Traveling click rates vs. ambient noise. Click rates shown were taken only while whales were traveling.