Echolocation use by Southern Resident Killer Whales (Orcinus orca) while foraging

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Introduction

The killer whale (*Orcinus orca*) is the largest member of the family Delphinidae. There are three ecotypes recognized in the Pacific Northwest: mammal-eating transients, fishing-eating residents, and offshores that are not well known but are presumed to eat fish and possibly mammals as well (NMFS 2008). There are currently no subspecies listed, but there is argument for subspecies to be recognized because of the diversity in behavior, ecology and vocalizations of the different populations around the world (NMFS 2008).

In November 2005, the Southern Resident killer whales (SRKW), which spend most of the summer months in the waters of Washington State and British Columbia, were listed as an endangered species under the Endangered Species Act of 1973. The National Marine Fisheries Service (NMFS), which is legally bound by the ESA to draft a recovery plan, found it difficult to determine which threats affect the whales the most or if they are threatened by a combination. Three main threats are believed to be primarily responsible for the decline in the population. They are a decrease in quality and quantity of prey, pollution and contaminants, and vessel disturbance and noise, including military sonar (NMFS 2008). Another purpose of the Recovery Plan is to designate critical habitats. Critical habitats are areas that the named species inhabit that contain physical or biological features essential to conservation (NMFS 2004). There are three areas that were named critical habitat for the SRKW: the Summer Core Area in Haro Strait and waters around the San Juan Islands, Puget Sound, and the Strait of Juan de Fuca (NMFS 2004). Some areas were not included due to insufficient information.

Killer whales are social animals which live in groups called pods (Bigg et al. 1987). Each pod is made up of one or more maternal groups with a female and her offspring (Ford 1989). The animals in each pod seem to communicate by group specific calls. The function of calls are not completely understood, but there are general types that can be categorized (Ford 1989). Ford (1989) describes the three different sound types of killer whales: whistles, pulsed calls, and clicks. Whistles are sounds based on tonal format with a continuous waveform that can have harmonics (Thomsen et al. 2001). Calls are pulsed sounds of abrupt and patterned shifts in pulsing rates that allows a wide variety of distinctive calls (Ford 1989). Clicks are brief pulses of sound used for echolocation and can vary in structure like duration and repetition rate (Ford 1989). Clicks are regularly used during foraging, most likely to navigate and locate prey (Ford 1989).

Killer whales are highly efficient predators that use both sight and echolocation clicks to locate prey before capturing them (Nichol and Shackleton 1996). Different prey choices among the different populations of killer whales around the world are accompanied by different foraging strategies and social structures that are learned traditions and have developed over many generations (Saulitis et al. 2000, and Ford et al.

1998). The Scandinavian herring-eating killer whales, for example, have high rates of sound production while foraging with intense clicks, calls and tail slaps with no periods of silence. This helps them herd the herring into tight schools close to the surface because herring have strong schooling behavior (Simon et al. 2007). The residents and transients of the Pacific Northeast are very specialized as well. Transients are practically silent when traveling and foraging because they rely on passive listening to detect prey. Their marine mammal prey has very good hearing and silence is required in order to keep from being detected (Ford et al. 1998). Residents however, are highly vocal when foraging and emit both social calls and echolocation click trains (Ford et al. 1998).

Echolocation clicks are sounds of high intensity and frequency. An echo bounces back to the animal which allows for the detection of possible prey. The clicks are projected from the animal's head in a highly directional beam which helps provide good target localization ability and strong echo returns from the target (Richardson et al. 1995). Clicks are very fast and only have a duration ranging from 0.8 to 13 milliseconds with the majority being greater than 4 milliseconds (Steiner et al. 1979). The frequency of the clicks ranges from below 2 kHz to 50 kHz but the peak energy ranges from 4 to 18 kHz (Barrett-Lennard et al. 1994 and Steiner et al. 1979). The use of echolocation has been studied for the last three decades (Au et al. 2007). Au et al. (2004) modeled the echolocation signals of Northern Resident killer whales and estimated the detection distance of a .78 m long Chinook to be at least 100 meters in calm conditions. The basic concept of how echolocation works is well documented with experimental evidence, but virtually nothing is known about the use and functional significance in the wild (Barrett-Lennard et al. 1994). Click rates have not been determined for killer whales but Barrett-

Lennard et al. (1994) found that click rates while foraging were the highest followed closely by traveling.

In order to study the use of echolocation when foraging, it is important to know when the whales are foraging. During foraging, whale groups typically spread out into moderately sized subgroups over several square kilometers. The subgroups swim and dive independently but travel in the same general direction (Ford and Ellis 2006, Hoelzel 1993). Often signs of feeding are quite subtle, and it is often difficult to identify foraging. Sometimes nondirectional swimming and erratic swimming can be observed to indicate that prey is being pursued (Nichol and Shackelton 1993, Hoelzel 1993). The whales have been found to frequently share prey caught by an individual with two or more other whales (Ford and Ellis 2006). Adult male killer whales share their prey less frequently, but were still found to bring their prey to the surface for consumption (Ford and Ellis 2006). The whales seem to benefit from the social behavior through facilitated food finding, but not necessarily cooperative capture (Hoelzel 1993).

The SRKW feed entirely on fish. An overwhelming majority of those fish are salmonids, and a large portion of those are Chinook (Ford et al. 1998). Ford and Ellis (2006) found that 95% of documented kills were Chinook and 5% Coho. These two species represent less than 1% of the available salmonids in the area, which further shows how specialized the SRKW are (Ford and Ellis 2006). Scientists suspect that Chinook are selectively hunted because of their large size, high fat content, and location. They can be found in coastal waters throughout the year (Ford et al. 1998). Knowing areas where these fish are commonly found would be very important to the residents of this area and make hunting for them easier.

Areas of productivity are important to be known by many different species and if there is a consistent trend then the animals can return to these areas and have a higher chance of finding food. These areas of high productivity have been referred to as “hot spots” and have many different variables (Gende and Sigler 2006). The most important thing for predator to have in a “hot spot” is persistence (Gende and Sigler 2006). Persistence can be affected by time, season, space, and bathymetry (Gende and Sigler 2006, and Hastie et al. 2004). Gende and Sigler (2006) did a study with Stellar sea lions and found that they had seasonal ‘hot spots’ but not in areas with the highest densities of prey. Instead the hot spots were in the areas that had persistent prey available instead of high densities. Hastie et al. (2004) found that bottlenose dolphins have ‘hot spots’ in areas with deeper water. It has also been suggested that killer whales use steep gradients while foraging.

It is understood that echolocation is used to locate prey, but there is very little understanding on how much it is used (Au et al. 2007). There have been some modeling studies of echolocation detection range, but little more is known. The click rates of killer whales have only been tested once and that study showed that click rates were highest during foraging (Barrett-Lennard et al. 1994). Knowing the click rates during different behaviors could help scientists acoustically identify behaviors of the whales instead of relying on surface activity. It can be very difficult to determine a pod’s behavior visually because the whales spend most of their time underwater, and most of the activities are difficult to see. Foraging is especially difficult to determine because this behavior is very subtle from the surface. Knowing the click rate for specific behavior states can help distinguish between behaviors with more certainty than just surface behaviors. It can also help scientists learn more about when and why echolocation is used with more certainty.

This experiment is designed to address two different questions. The first is to determine click rates during different behavior states and compare them to each other. If there is a significant difference between click rates in different behavior states, this will provide scientists with a better way to determine behavior states in future research. Furthermore, a higher click rate while foraging will show that echolocation clicks are important for finding food. The second question will try to determine possible foraging “hot spots” for the whales. Based on anecdotal information the “hot” foraging area has been determined to be from Salmon Bank along the west side of San Juan Island up to Andrews Bank. NMFS has declared critical habitats for the SRKW in the Recovery Plan (NMFS 2008). Any evidence provided to further prove foraging hot spots within the boundaries of the critical habitat will be useful information

Methods

Data Collection

This research was conducted from May 10th to May 25th 2009 in Haro Strait, mostly along the west side of San Juan Island. There were nine days of recordings with the whales. Data was collected on a 42‘ catamaran named the *Gato Verde*. There were five behaviors documented. They were foraging, milling, resting, traveling and playing. The behaviors defined by NOAA (2004) were used. Foraging is flank or nonlinear orientation, non-directional, spread formations and occasional fast sporadic movements. Milling is nonlinear orientation that is nondirectional and slow paced. Resting is flank or nonlinear orientation that is directional with contact or tight distances between whales.

During resting, the whales are also highly synchronous and slow moving. Traveling is any orientation that is directional and could be slow medium or fast paced. Finally, play can include any combination of orientation, direction and speed. It also includes events like object play, social interactive play, including touching, breaching and other percussive events, or solitary play. For more details refer to the Southern Resident Killer Whale Behavior Workshop (NOAA 2004).

The behavior of the whales was recorded, and GPS was simultaneously used to record the latitude and longitude of the research vessel. Recording their behavior started at the same time the hydrophone recording started. GPS points were recorded at the start and stop of each recording and at any time the whales changed behaviors. At the start of the recording period the date, time, and initial behavior were documented in real time and any change in behavior was noted in real time as well. The boat's orientation to the whales was also recorded. Any recordings when the whales were traveling away from the boat were not analyzed because clicks are relatively narrow (Au et al.). A Labcore hydrophone array consisting of four hydrophones that are each approximately ten meters apart was towed behind the boat and weighted down to decrease flow noise. Recordings were continuous with two, two channel Sound Devices 702 digitally at a sampling rate of 44.1 kHz. The array was calibrated with a calibrated Interocean Systems Model 902 hydrophone with the gains of the Sound Device set at 36.0 dB.

Whales present were either identified on the spot or photos were taken in order to try and identify whales later. The pod we were with was identified for each recording. When recording the behaviors of the whales, there was an assumption that the whole pod is present and not just subgroups visible, because when a pod divides into subgroups, the general activities and direction of travel are still the same for all individuals within the pod, even though the distance between some individuals can be several kilometers (Hoelzel 1993). The behavior observed by the majority of the pod is the behavior that was recorded. The second part of the research is based on anecdotal stories.

The “hot” foraging area was defined after talking to experienced whale watchers and getting the opinions of people who have been watching these whales for years. Captain Jim Maya, owner of Maya’s Westside Charters, has been watching these whales for years. He said the whales have various areas where they commonly forage along the southern coast of San Juan Island. He also said that when heading north along the coast they frequently turn around at Andrews Bay and forage while heading south. Others have confirmed this trend. I decided to define the foraging “hot” foraging area for this study from Salmon Bank to Andrews Bay. The traveling area is North of Andrews Bay to the North end of Henry Island. Locations that were outside of this area were not considered in the analysis. See map below

The “hot” foraging area used for research is from Salmon Bank to Andrews Bay. The Traveling area is from Andrews bay to the north end of the Island.

Data Analysis

The data was analyzed using Raven Lite, a program designed by Cornell University. The sound files were separated into one minute sound files. Each minute of recording was opened in Raven Lite with the time series and spectrogram (See Fig. 1). The spectrogram was looked at using the *hot* color setting. The FFT rate used was 3041. Clicks were counted for each minute using the spectrogram. In order for a click to count the click needed to be both seen and heard. This was necessary to ensure that the clicks originated from the whales, and not something else such as a boat. Clicks from whales were easily picked out from other foreign noise. The time series was only used to count click trains. Click trains appear as blurs in the spectrogram (see Fig 2) and individual clicks can not be counted. When the time series is zoomed in individual clicks can be easily counted. When the background noise was too loud to hear the clicks that minute was not analyzed. Any minute that contained “clicks” that could not be positively identified as a click coming from a whale was also not analyzed.

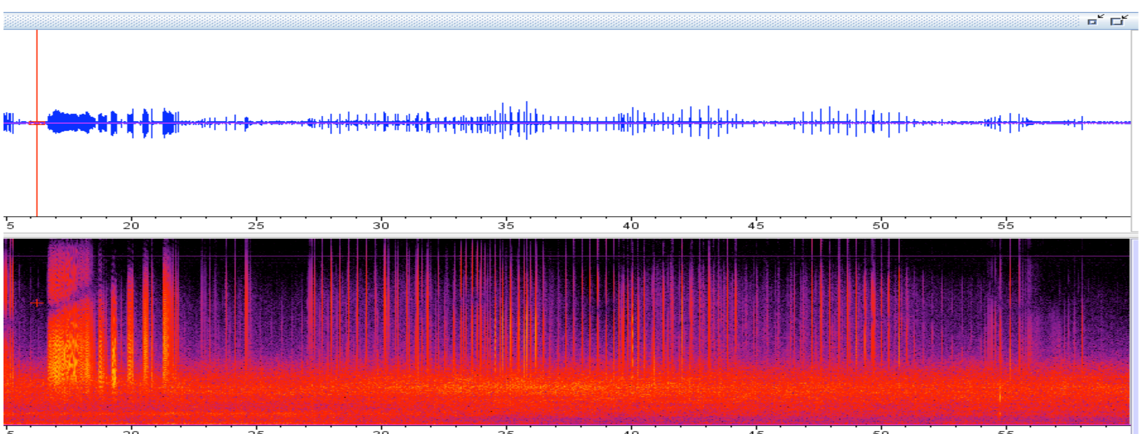

Figure 1
Example of Time Series (top) and Spectrogram (bottom) in Raven Lite. The x-axis is elapsed time in seconds and y-axis in the lower portion of the figure is frequency in kHz. Hotter colors mean louder

sounds. Between 15 and 25 seconds there is a series of click trains followed. The rest are single clicks. The upper trace shows the amplitude of the recorded sound as a function of time.

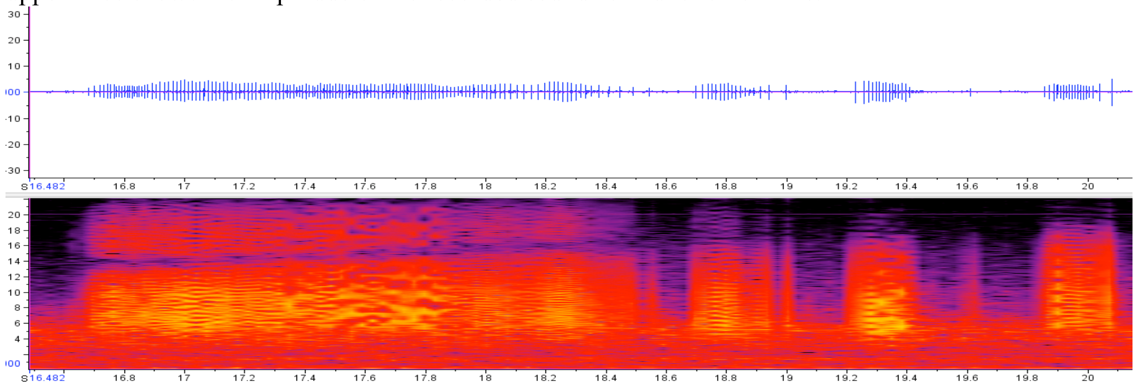

Figure 2
Zoomed in click train. Time series (top) used to count individual clicks. Spectrogram (bottom) too blurred to count individual clicks. The clicks are blurred because my FFT rate was 3041. As you increase the FFT rate the frequency becomes more accurate but the time resolution gets blurred.

Results

Click Rates for behaviors

There were a total of 9 days of recordings with the whales with 1,057 minutes of recording. There were 404 minutes where clicks were able to be analyzed. Of those minutes, 77 were foraging, 243 were traveling, 38 were milling, 35 were resting and 11 were playing. The average click rates for each behavior was: 89.5 clicks per minute for foraging, 70.0 clicks per minute for traveling, 49.6 clicks per minute for milling, 19.1 clicks per minute for resting, and 425.8 clicks per minute for playing (see Figure 3).

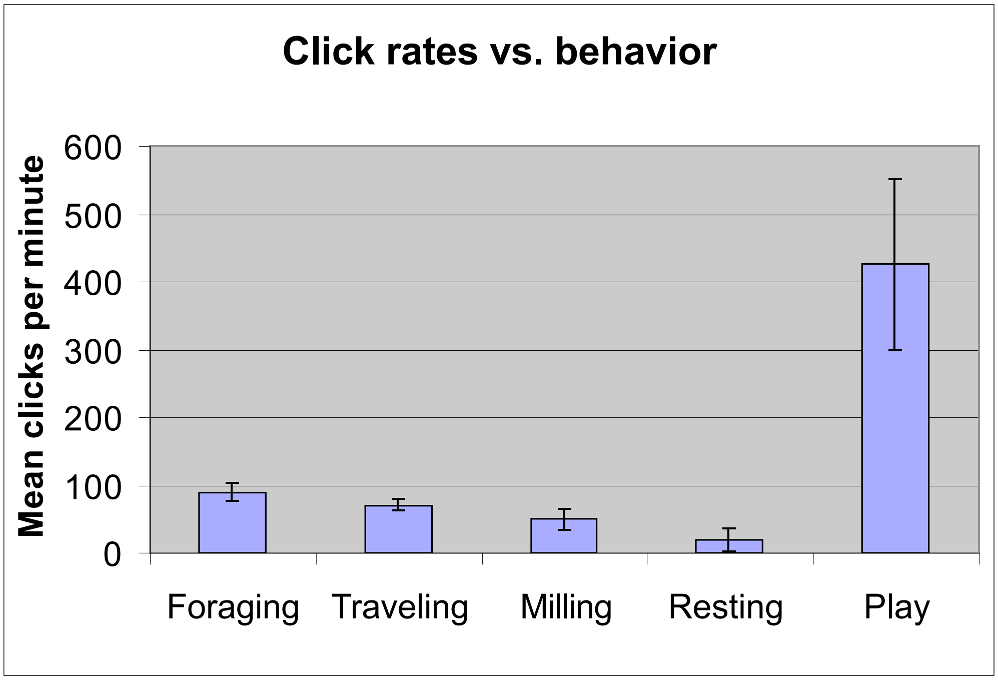

Figure 3
Mean click rate for each behavior with 95% confidence interval error bars.

I decided to run a one-way ANOVA because the independent variable is categorical and has more than two groups. The distribution was not normal but after transforming the data the distribution was close to normal and still showed significance. The one-way ANOVA showed significant difference in click rates between behaviors ($p < 0.001$, $F_{4, 403} = 73.56$) in both the transformed data and the original data. In order to test to see which behaviors were significantly different from each other a Tukey multiple pair wise comparison was run. Foraging was significantly different from milling ($p = 0.0388$, $T = -2.8$), resting ($p < 0.001$, $T = -4.8$), and play ($p < 0.001$, $T = 14.6$). Play was statistically significant from milling ($p < 0.001$, $T = 15.4$), resting ($p < 0.001$, $T = -16.5$), and traveling ($p < 0.001$, $T = -16.1$). Resting was significantly different from traveling ($p < 0.001$, $T = 4.0$).

Foraging "hot" foraging areas

There was no significant difference between the amount of time spent foraging in the “hot” foraging area compared to the traveling area. Figure 4 shows the number of times we were with the whales in the foraging “hot” foraging area compared to traveling area. As there was no significant difference in the amount of time spent foraging I compared the click rates in both areas.

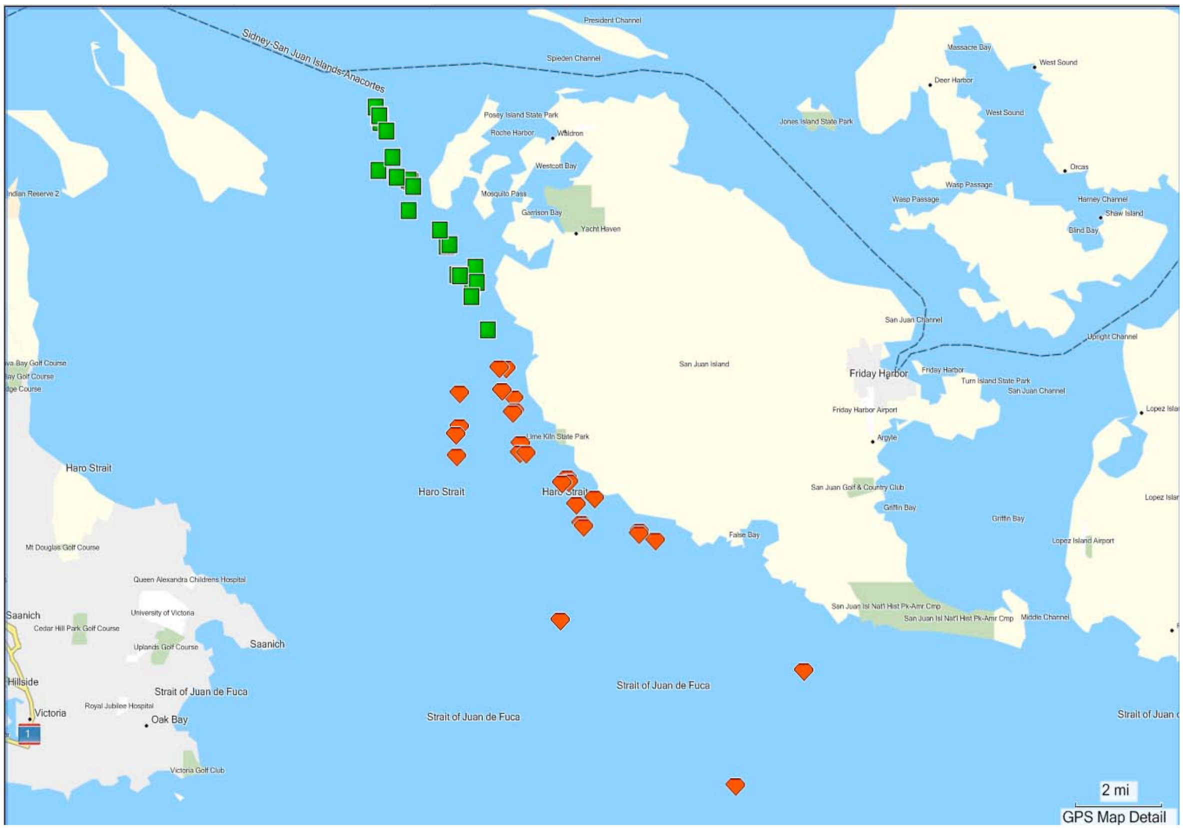

Figure 4
The red diamonds indicate the times the whales were recorded in the “hot” foraging area. The green squares indicate when the whales were recorded outside of the “hot” foraging area. (This map was generated in Map Source).

There were 269 analyzed minutes recorded from these two areas; 204 of those minutes were recorded in the traveling area and 65 minutes were recorded in “hot” foraging area area. The average click rate for the traveling area was 76 clicks per minute and the click rate in the “hot” foraging area was 125 clicks per minute regardless of behavior (see Fig. 5). A one-way ANOVA was used to determine that the whales’ mean click rate in the “hot” foraging area was significantly higher than the click rate outside of the “hot” foraging area ($p < 0.001$, $F_{1, 8} = 0.25$).

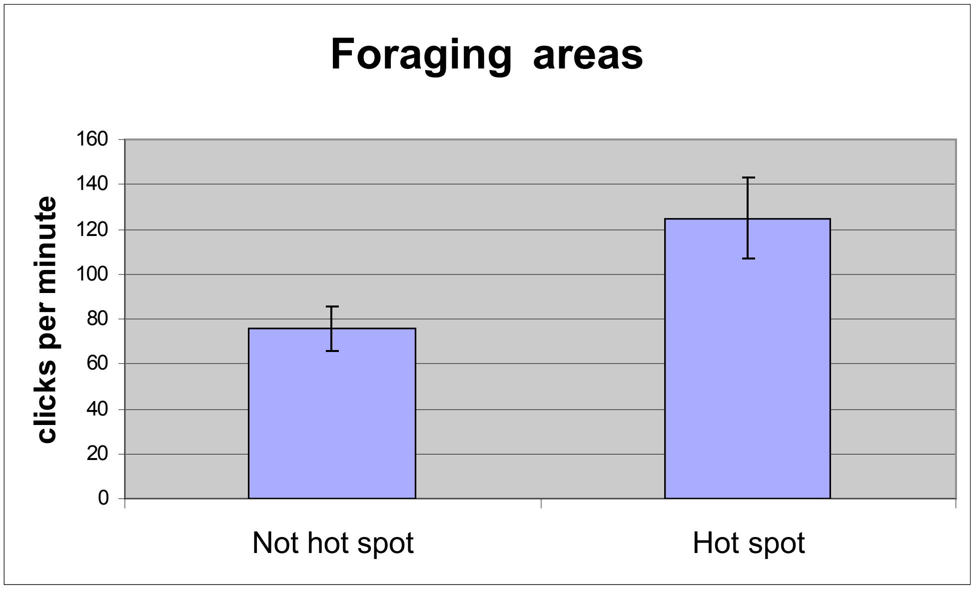

Figure 5
The average click rate in the “hot” foraging area is compared to the average click rate outside of the “hot” foraging area. The error bars are for a 95% Confidence interval.

Conclusion

Scientists know that echolocation is used and have done many experiments to answer the “what” and “how” but not many people have asked “when” (Barrett-Lennard et al.). This experiment has started to address this question. I have found that the click rates were highest during playing by a very large margin, and then foraging had the next highest click rate. I was expecting foraging to have to highest click rate out of all of the behaviors. There is a possibility that the click rate for playing is incorrect because the sample size is very small and might not show the real average of click rates for this behavior. The click rate for play could also be a true representation. Clicks could be part of their communication. As I was analyzing clicks I often noticed clicks in the middle of calls. There were also many occasions when a click train preceded a call. Since I didn’t localize I don’t know if these clicks and calls came from the same whale or if it was in fact two whales making the two noises at the same time. This would be an interesting question to pursue further. Foraging, however, did have the second highest click rate.

Foraging was not significantly different from traveling but the mean was higher than traveling. Foraging was significantly different from the rest of the behaviors. Barrett-Lennard et al. (1996) found similar results in click rates for foraging and traveling. They found that the residents clicked more frequently when foraging, and they also report that traveling had a relatively high average click rate. Foraging was expected to have a high click rate because it is used to find the salmon. I was not anticipating traveling click rates to be as high as they were but now that I have looked at the data it makes sense. Echolocation is used to find fish as well as for navigation. One discrepancy with my data collection is the fact that I did not consider the number of whales in the area when recording. Barrett-Lennard et al. (1996) found that echolocation use per individual decreased with increasing group size. So theoretically the click rates should generally stay the same despite the number of whales present. So I feel that these click rates are an accurate representation of the rates for the behaviors.

Knowing general click rates for each behavior is important for future research because we still don’t know why whales click. Having consistent click rates for different behaviors can also help scientists understand a little more about why whales use echolocation clicks. We have assumptions that clicks are just used for finding food and navigating but there hasn’t really been much research on it. More research needs to be done on click rates for the different behaviors. There should be larger sample sizes and the results need to be reproduced. Once click rates are generalized for each behavior it would make it possible to monitor behaviors from land using strategically placed hydrophones. Another important issue that should be studied more is where the whales forage.

If the whales frequently visit the same areas in order to hunt then those areas should be considered vital for their survival as a population. There was not a significant difference in the time spent foraging in the "hot" foraging area compared to the traveling area. This was a very small sample size. We were only with the whales on nine different days and only three of those days were spent foraging. In order to really determine if the whales forage more in particular areas the sample size needs to be much bigger. Also after talking with more people, I realized that there are specific spots that are common for foraging. Most of these spots were included in my "hot" foraging area but one spot, Kellet Bluff, which was part of the traveling area. Looking back at the data the one foraging event recorded in the traveling area was at Kellet Bluff. For future studies instead of doing large foraging and traveling areas the area can be split into smaller sections so that there aren't foraging areas in the larger traveling areas. Smaller "hot spot" areas would also allow for a more detailed idea of what areas are really important to the whales for foraging. Future research should focus more on collecting detailed information on where the fish are in order to determine if foraging hot spots rely more on bathymetry or on the movement of the fish or both.

Dealing with an endangered species is difficult because there is such a limited population and so much is unknown. What complicates this situation even more is the killer whales' main food source is also endangered. More research needs to be done on their food resource and their distribution patterns. If there are hot spots for the SRKW then those areas should be protected in order to preserve the good hunting grounds of this species. NOAA has already begun to address this concern but more research should be done.

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