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Citation: The Journal of the Acoustical Society of America **151**, 1651 (2022); doi: 10.1121/10.0009752
View online: https://doi.org/10.1121/10.0009752
View Table of Contents: https://asa.scitation.org/toc/jas/151/3
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Effects of duty cycles on passive acoustic monitoring of southern resident killer whale (*Orcinus orca*) occurrence and behavior

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ABSTRACT:
Long-term passive acoustic monitoring of cetaceans is frequently limited by the data storage capacity and battery life of the recording system. Duty cycles are a mechanism for subsampling during the recording process that facilitates long-term passive acoustic studies. While duty cycles are often used, there has been little investigation on the impact that this approach has on the ability to answer questions about a species' behavior and occurrence. In this study, the effects of duty cycling on the acoustic detection of southern resident killer whales (SRKW) (*Orcinus orca*) were investigated. Continuous acoustic data were subsampled to create 288 subsampled datasets with cycle lengths from 5 to 180 min and listening proportions from 1% to 67%. Duty cycles had little effect on the detection of the daily presence of SRKW, especially when using cycle lengths of less than an hour. However, cycle lengths of 15–30 min and listening proportions of at least 33% were required to accurately calculate durations of acoustic bouts and identify those bouts to ecotype. These results show that the optimal duty cycle depends on the scale of the research question and provide a framework for quantitative analysis of duty cycles for other marine species.

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(Received 28 September 2021; revised 28 January 2022; accepted 13 February 2022; published online 11 March 2022)

[Editor: Colleen Reichmuth] Pages: 1651–1660

I. INTRODUCTION

Cetaceans are difficult to study using visual survey methods because they spend a significant amount of time underwater, dive to deep depths, and often move quickly. Cetaceans use sound for communication, foraging, and to obtain information about their environment (Richardson *et al.*, 1995), which allows many species to be detected through passive acoustic monitoring (PAM). Unlike visual survey methods, PAM facilitates long-term observation of cetaceans because it can operate in poor weather conditions, at night, and in study areas that are difficult to reach, while causing little interference in the subject's behavior (Au *et al.*, 2013; Oswald *et al.*, 2016; Richard *et al.*, 2017; Širović *et al.*, 2009).

Killer whales (*Orcinus orca*) are an ideal candidate for PAM because of their well-studied acoustic repertoire. Killer whales are an acoustically active species and produce a variety of acoustic signals, including echolocation clicks, whistles, and pulsed calls (Deecke *et al.*, 2005; Ford, 1991; Riesch *et al.*, 2006; Samarra *et al.*, 2010). Some pulsed calls, known as discrete or stereotyped calls, have distinctive structural properties, which have been catalogued (Ford, 1987). These stereotyped calls can be used to identify three distinct lineages, or ecotypes, of killer whales in the northeastern Pacific: residents, transients, and offshores. Furthermore, two sympatric populations of resident killer whales in the northeastern Pacific, the northern, and southern residents, as well as their smaller, matrilineal groupings (pods and clans) can be reliably distinguished acoustically based on group-specific repertoires of stereotyped calls (Ford, 1991).

Long-term passive acoustic data are essential for observing marine mammals because their acoustic behavior can vary over spatial scales, by season, time of day, group size or composition, and motivational state (Lammers and Oswald, 2015; Van Opzeeland *et al.*, 2010; Parks and Clark, 2008). However, long-term acoustic data can be difficult to acquire. Many long-term PAM studies use fixed autonomous recorders (Van Parijs *et al.*, 2009), where the hydrophone and recorder are fixed to the seafloor. The data are stored and archived on the recorder and then recovered and processed on land (Sousa-Lima *et al.*, 2013). Inherent to this approach are constraints on data storage, battery capacity, and the ability to maintain or replace recorders during a long-term study. Additionally, even when data storage is not a limiting factor, long-term acoustic studies often produce large datasets that are time consuming and labor intensive to analyze in their entirety.

Duty cycling is a tool that can facilitate long-term acoustic recordings. A duty cycle is a mechanism for

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subsampling during a recording period, where the recorder is only collecting data for a specified amount of time over a repeating cycle. Duty cycles are described by the length of the cycle and the proportion of the cycle where the recorder is actively collecting data. For example, in a duty cycle with a cycle length of 5 min and a listening proportion of 0.1, 30 s of data would be recorded every 5 min. While duty cycles are frequently used in long-term studies of cetaceans, the selection of cycle length or listening proportion is not consistent. For example, in passive acoustic studies of killer whales that use duty cycles, cycle lengths range from 5 to 240 min, and listening proportions from 0.1 to 0.67 (Hannay *et al.*, 2013; Hanson *et al.*, 2013; Rice *et al.*, 2017; Richard *et al.*, 2017; Riera *et al.*, 2019). Additionally, in most published studies using duty-cycled data, the selection of the duty cycle is only justified based on the storage capacity and battery life of the recorder and not related to the acoustic behavior of the focal species (e.g., Diogou *et al.*, 2019; Hanson *et al.*, 2013; Lammers *et al.*, 2017).

The selection of duty cycle characteristics is important because it cannot be assumed that the proportion of recording time missed by a given duty cycle is equivalent to the proportion of missed detections as marine mammals have variable patterns of acoustic behavior and do not produce sound continuously. For example, a study of North Atlantic right whales (*Eubalaena glacialis*) found that subsampled data did not accurately capture species presence or calling rate when calling activity was low or when there were distinct diel patterns in calling behavior (Thomisch *et al.*, 2015). Without an understanding of the effect of duty cycle on passive acoustic detections, researchers may select duty cycles that are inappropriate for the acoustic behavior of their focal species.

In addition, the impact of duty cycles on the results of investigations of specific research questions may depend on the scale of the research question itself. For example, passive acoustic methods can be used to monitor cetacean presence in habitats over long time scales. These types of investigations often require broad-scale data, such as daily presence/absence (e.g., Hanson *et al.*, 2013; Riera *et al.*, 2019). However, more detailed information about acoustic behavior may be required for questions that depend on detail at shorter time scales. For instance, the number of signals per hour or minute has been used to determine diel patterns in acoustic behavior for many species (e.g., Stafford *et al.*, 2005; Oswald *et al.*, 2011). Missed acoustic detections caused by using an inadequate duty cycle could impact questions requiring fine-scale data differently than questions relating to broad-scale presence.

Some research questions may require an even finer-scale level of detail, such as the study of acoustic bouts. A bout is a temporal cluster of a specific behavior (Martin and Bateson, 2017), in this case acoustic signals. Resident killer whales and other cetaceans have been found to produce social sounds in bouts (Miller *et al.*, 2004; Rekdahl *et al.*, 2015). Analysis of bouts of social sounds can provide information about the behavioral context and complexity of cetacean social communication (e.g., Janik *et al.*, 2013; Miller *et al.*, 2004; Rekdahl *et al.*, 2015) and may reveal fine-scale details of habitat use when visual observation is not possible (e.g., Emmons *et al.*, 2021; Riera *et al.*, 2019). Missed acoustic detections caused by using an inadequate duty cycle during recording could impact the way acoustic behavior is split into bouts, leading to misunderstandings of the complexity of social interactions, and under- or overestimates of species encounters.

Previous studies have addressed the impact of duty cycles on the analysis of acoustic data; however, the applicability of their results has been limited. This is due to the testing of a small number of duty cycles (Riera *et al.*, 2013), a focus on baleen whale species which have a different scale of acoustic behavior than odontocetes (Thomisch *et al.*, 2015), or limiting the research question to broad-scale presence of odontocete species (Stanistreet *et al.*, 2016). The purpose of the current study is to address some of these limitations by examining how duty cycling impacts the detection of southern resident killer whale (SRKW) calls and whistles and how this affects our ability to answer questions about occurrence and behavior on several time scales. To achieve this, 288 subsampled datasets were simulated from a continuous acoustic recording of SRKW using a variety of listening proportions and cycle lengths. These subsampled datasets were used to study daily presence, diel patterns in acoustic detections, and bouts of acoustic behavior. The results from these subsampled datasets were then compared to each other and to the results from the continuous dataset.

II. METHODS

A. Study site

Recordings were made using a seafloor-mounted hydrophone in the Haro Strait. It was located 70 m offshore on the west side of San Juan Island, Washington, near the U.S/Canada border (48°30′ N, 123° 8′ W). The hydrophone was placed at 23 m depth and attached to a polyvinyl chloride (PVC) pipe mooring, approximately 1 m off the seafloor. Substrate in the hydrophone location consists of boulders, gravel, and marine vegetation (Veirs *et al.*, 2016).

B. Data collection

A Reson TC4032 hydrophone (170 dB re 1 V/μPa, +/− 3 dB from 0.01 to 100 kHz, Teledyne Marine, Slangerup, Denmark) was connected to a land-based listening station in the Lime Kiln Lighthouse on San Juan Island using a 100 m cable. Single channel recordings were made using a 250 kHz sampling rate, with a 16-bit resolution. A high-pass filter at 10 Hz was applied before recording. Recordings were stored in 1 min consecutive .wav files. The hydrophone was deployed prior to the study and replaced on September 14, 2018. Continuous recordings were obtained over 112 days between July 12, 2018 and October 31, 2018.

C. Analysis of continuous data

An automated detector, the PAMGuard (https://www.pamguard.org) whistle and moan detector (WMD)

(Gillespie *et al.*, 2009), was used to detect killer whale pulsed calls and whistles in the recordings. Each PAMGuard detection was manually verified both aurally and visually using spectrograms (Hann window, 2048 point fast Fourier transform, 50% overlap) in Raven Pro 1.6.1 (http://ravensoundsoftware.com/) (Center for Conservation Bioacoustics, 2019). The WMD was set to sensitive settings to minimize missed detections which led to a high false-detection rate (42% of WMD detections during the study period were false). False detections were removed, and only manually verified killer whale calls and whistles were used in further analysis. The start and end times in UTC as well as the duration of each signal in seconds were manually logged by the researcher. Overlapping signals were logged separately. When stereotyped calls were present and clearly distinguishable, they were identified to their individual call type using visual and aural cues. Published SRKW and west coast transient killer whale call catalogues were used to identify stereotyped pulsed calls to ecotype (Deecke *et al.*, 2005; Ford, 1987). When non-stereotyped pulsed calls or whistles were present, they were catalogued as either a pulsed call or a whistle.

A bout criterion interval (BCI) was used to determine the interval between calls and/or whistles that would define a new bout. Using R 3.6.3 (R Core Team, 2021), gaps between signals were calculated in seconds and then used to plot a log-survivorship curve. The log-survivorship curve was used to calculate the BCI using the equation by Slater and Lester (1982), where N_W is the number of within bout gaps and λ_W is the rate of the process generating the within-bout gaps. Similarly, N_B and λ_B are the number of between-bout gaps and the rate of the process generating them [Eq. (1)],

$$BCI = \frac{1}{\lambda_W - \lambda_B} \log_e \frac{N_W \lambda_W}{N_B \lambda_B}. \tag{1}$$

Using the calculated BCI, the continuous data were split into bouts of acoustic behavior and stereotyped calls were used to determine the ecotype of the killer whales producing the bout. If no stereotyped calls were present within the bout, it was classified as unknown. There were no bouts that contained both SRKW and West Coast transient killer whale stereotyped calls. Due to the small sample size of West Coast transient killer whale bouts, only SRKW bouts were used for further analysis. All unknown bouts were removed.

TABLE I. Amount of recording time per cycle (in seconds) for each tested duty cycling regime and the total number of cycles in each 24 h day.

		Recording time (s)								
Listening proportion		0.10	0.125	0.167	0.2	0.25	0.33	0.5	0.667	Total cycles/day
Cycle length (min)	5	30	37.5	50	60	75	100	150	200	288.0
	10	60	75	100	120	150	200	300	400	144.0
	15	90	112.5	150	180	225	300	450	600	96.0
	20	120	150	200	240	300	400	600	800	72.0
	25	150	187.5	250	300	375	500	750	1000	57.6
	30	180	225	300	360	450	600	900	1200	48.0
	35	210	262.5	350	420	525	700	1050	1400	41.1
	40	240	300	400	480	600	800	1200	1600	36.0
	45	270	337.5	450	540	675	900	1350	1800	32.0
	50	300	375	500	600	750	1000	1500	2000	28.8
	55	330	412.5	550	660	825	1100	1650	2200	26.2
	60	360	450	600	720	900	1200	1800	2400	24.0
	65	390	487.5	650	780	975	1300	1950	2600	22.2
	70	420	525	700	840	1050	1400	2100	2800	20.6
	75	450	562.5	750	900	1125	1500	2250	3000	19.2
	80	480	600	800	960	1200	1600	2400	3200	18.0
	85	510	637.5	850	1020	1275	1700	2550	3400	16.9
	90	540	675	900	1080	1350	1800	2700	3600	16.0
	95	570	712.5	950	1140	1425	1900	2850	3800	15.2
	100	600	750	1000	1200	1500	2000	3000	4000	14.4
	105	630	787.5	1050	1260	1575	2100	3150	4200	13.7
	110	660	825	1100	1320	1650	2200	3300	4400	13.1
	115	690	862.5	1150	1380	1725	2300	3450	4600	12.5
	120	720	900	1200	1440	1800	2400	3600	4800	12.0
	125	750	937.5	1250	1500	1875	2500	3750	5000	11.5
	130	780	975	1300	1560	1950	2600	3900	5200	11.1
	135	810	1012.5	1350	1620	2025	2700	4050	5400	10.7
	140	840	1050	1400	1680	2100	2800	4200	5600	10.3
	145	870	1087.5	1450	1740	2175	2900	4350	5800	9.9
	150	900	1125	1500	1800	2250	3000	4500	6000	9.6
	155	930	1162.5	1550	1860	2325	3100	4650	6200	9.3
	160	960	1200	1600	1920	2400	3200	4800	6400	9.0
	165	990	1237.5	1650	1980	2475	3300	4950	6600	8.7
	170	1020	1275	1700	2040	2550	3400	5100	6800	8.5
	175	1050	1312.5	1750	2100	2625	3500	5250	7000	8.2
	180	1080	1350	1800	2160	2700	3600	5400	7200	8.0

D. Analysis of subsampled data

A total of 288 datasets with different duty cycling regimes were constructed by subsampling the continuous data according to 36 cycle lengths (5–180 min) and 8 listening proportions (0.10–0.67) (Table I). All subsampling and statistical analyses occurred in R version 3.6.3 (R Core Team, 2021) and code can be made available on request from the authors. Each duty cycle began on July 12, 2018 at 0:00 UTC and ended on October 31, 2018 11:59 UTC. It was assumed that the recorder was turned on at the beginning of each cycle, remained on for the duration of the cycle's recording time, and then was off until the beginning of the next cycle. If a detection of a SRKW whistle or pulsed call from the continuous data fell within the recording period of a duty cycling regime, it was included in the subsampled dataset for that duty cycling regime. To allow for signals that are only partially captured by the subsampled data but are still able to be identified as SRKW signals, detections where at least 75% of the duration of the acoustic signal was within the recording period were included in the subsampled dataset. This threshold was set because 75% of the duration of a call provides sufficient information for that signal to be identified to ecotype.

Acoustic detections from each subsampled dataset were split into bouts using the BCI identified from the continuous data as the shortest interval between bouts. Both the gaps between acoustic signals during each recording time as well as the gaps between recording times were compared to the BCI and used to split acoustic detections into bouts. If the time the recorder was off was longer than the BCI, each recording period was counted as a separate bout even if there were acoustic detections immediately before and after the gap between recordings. If bouts contained SRKW stereotyped calls, they were classified as SRKW bouts and if not, they were classified as unknown.

1. *Effects of duty cycles on killer whale presence*

For each day where SRKWs were detected in the continuous data, the presence/absence of SRKWs was logged for the subsampled datasets. To model the probability of correct detections of daily presence, a binomial generalized linear mixed model (GLMM) with a logit link function was used. This model was fit using the R package lme4 (Bates *et al.*, 2015). Cycle length and listening proportions were used as fixed covariates. To incorporate the variability in acoustic behavior by day, day was used as a random intercept which was assumed to be normally distributed. Cycle lengths were divided by 100 before fitting the model to account for the difference in scale between the covariates.

2. *Effects of duty cycles on diel patterns*

The presence of any diel patterns in the hourly detection of calls and whistles was investigated in the continuous data and each subsampled dataset. For this analysis, only days where SRKW acoustic signals were detected were included. Additionally, of those days, only days in which less than half an hour was missing from the continuous recordings were included. All SRKW acoustic detection times were converted to Pacific Daylight Time (PDT, UTC-7) from UTC. Then, the mean number of acoustic signals detected per hour (hourly detection rate) was calculated for each hour of each day used in this analysis. Days were split into three light regimes defined by the altitude of the sun based on data from the United States Naval Observatory (2019). Due to the changing times of sunrise and sunset over the course of the study, the light regimes included different hours for each month of the study (Table II).

The mean hourly detection rate (MDR_{LD}) was calculated for each light regime on a given day. Additionally, the mean hourly detection rate was calculated for each day of data used in this analysis (MDR_D). To account for the differences in acoustic behavior between days, the adjusted mean hourly detection rate ($AMDR_{LD}$) for each light regime on each day was calculated by subtracting the mean hourly detection rate per day from the mean hourly detection rate for each light regime on that day [Eq. (2)],

$$AMDR_{LD} = MDR_{LD} - MDR_D. \tag{2}$$

A one-way analysis of variance (ANOVA) and *post hoc* Tukey tests were used to test the null hypothesis that there was no difference in the adjusted mean hourly detection rates between light regimes.

3. *Effects of duty cycles on the detection and identification of bouts*

To model the effects of duty cycles on the total number of bouts detected, a negative binomial GLM (generalized linear model) with a log link function was fit using the R package (https://www.R-project.org/) *MASS* (Modern Applied Statistics with S, https://www.stats.ox.ac.uk/pub/MASS4/) (Venables and Ripley, 2002). A negative binomial distribution was used to account for overdispersion. This model included the total number of bouts as the response, and the cycle length and listening proportion as predictors. A Pearson correlation coefficient was used to examine the relationship between the maximum bout duration and the length of recording time during each cycle period. Additionally, median bout durations were modeled with a linear regression with median bout duration as the response and cycle length and listening proportion as the predictors. Errors in this model were assumed to be normally distributed. A non-linear pattern was present in the residuals, so the square of each term was also added to the model. Finally, to model the effects of using subsampled data on the proportion of bouts that could not be classified as SRKW bouts, a binomial GLM with a logit link function was used. The proportion of total bouts that were classified as unknown was the response and the cycle length and listening proportion were predictors.

III. RESULTS

A. Continuous data

A total of 2517 h of recordings from July 12, 2018 to October 31, 2018 were analyzed for this study. Due to technical issues, two full days of recordings were missing during

TABLE II. Definitions and hours included for each light regime used in the analysis of diel patterns of acoustic behavior. All times are based on the location of the hydrophone (48° 30’ N, 123° 8’ W) and are listed in PDT.

Light regime	Definition	July	August	September	October
Light	Hours when the altitude of the sun was greater than 0° above the horizon	05:00– 20:59	06:00– 19:59	06:00– 18:59	07:00–17:59
Twilight	Hours when the altitude of the sun was between 0° and −12° below the horizon	03:00– 04:59 and 21:00– 22:59	04:00–05:59 and 20:00–20:59	05:00–05:59 and 19:00 to 19:59	06:00–06:59 and 18:00–18:59
Dark	Hours when the altitude of the sun was less than −12° below the horizon	23:00–02:59	21:00–03:59	20:00–04:59	19:00–05:59

the study period and 12 additional days during the study period were missing more than half an hour of data. Killer whale pulsed calls and whistles were detected on 46 out of 110 days during the study period.

The minimum time gap between bouts (BCI) was calculated to be 569 s (9.48 min). Using this interval, acoustic detections from the continuous data were split into 155 bouts. Of these 155 bouts, 95 were identified as SRKW, 15 as west coast transient killer whales, and 45 were unknown. A total of 60 bouts were removed (West Coast Transients and unknown) and were not included in any additional analysis. This accounted for 12.4% of the total duration of recorded bouts. SRKW bouts were detected on 36 days during the study period. The durations of SRKW bouts were right-skewed, with some having a duration of greater than 100 min, but most having durations of less than 50 min. The median duration of SRKW bouts was 13.95 min with an interquartile range of 5.28–39.16 min.

B. Effects of duty cycles on SRKW presence

1. Daily SRKW presence

Based on the binomial GLMM with a logit link function, duty cycle length and listening proportion were statistically significant predictors of the probability of correctly detecting daily SRKW presence ($p < 0.001$). The estimated standard deviation for the random effect of date was 2.68 (bootstrapped 95% confidence interval: 1.93–3.35). For all cycle lengths, increasing the listening proportion increased the probability of correctly detecting daily SRKW presence. However, shorter cycle lengths led to high probabilities of correctly detecting SRKW daily presence, regardless of the listening proportion (Fig. 1).[1]

2. Effects of duty cycles on detection of diel patterns

In the continuous data, the adjusted mean hourly detection rate was higher during light hours than during dark or twilight hours, though there was no evidence that this difference was statistically significant (one-way ANOVA, $F = 1.23$, $p = 0.30$).

A significant difference in adjusted mean hourly detection rate between light regimes was found in 13 of the 288 subsampled datasets (one-way ANOVA, $p < 0.05$). All of these datasets had cycle lengths of 40 min or longer, and all but one had listening proportions of less than 0.5. *Post hoc* Tukey tests for these datasets revealed either a difference ($p < 0.05$) between light and dark categories ($n = 1$), light and twilight categories ($n = 6$), or did not find differences between any of the three categories ($n = 6$).

3. Effects of duty cycles on bout detection and identification

Based on a negative binomial GLM with a log-link function, both cycle length and listening proportion were statistically significant predictors of the total number of SRKW bouts ($p < 0.001$). Theta for the negative binomial family was estimated to be 27.12 (standard error: 2.94). The total number of bouts decreased with increasing cycle lengths and increased with the listening proportion (Fig. 2).[1]

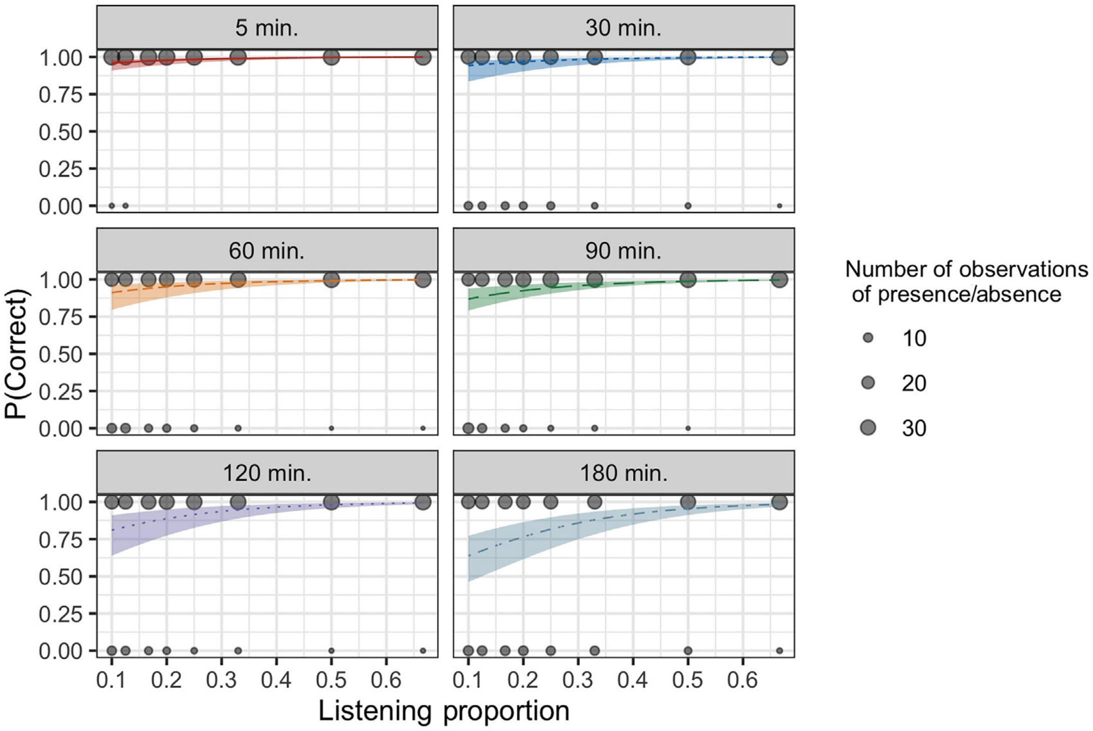

FIG. 1. (Color online) Predicted probability of correct detection of daily presence according to listening proportion for six selected cycle lengths from binomial GLMM with logit link function. Shaded area represents 95% confidence intervals generated using bootstrap methods with 100 simulations. Circles represent actual success (1) and failure (0) of detecting daily presence given the listening proportion and cycle length.

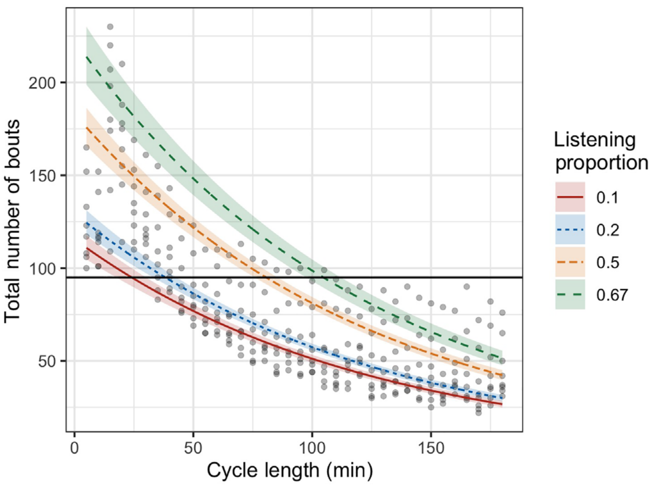

FIG. 2. (Color online) Total number of bouts found in subsampled datasets according to cycle length. Lines represent predicted total number of bouts from a negative binomial GLM with a log link function given a selected listening proportion of 0.1, 0.2, 0.5, and 0.67. Shaded areas indicate 95% confidence intervals. The horizontal line signifies the total number of SRKW bouts (95) found in the continuous dataset. Circles represent actual number of SRKW bouts in subsampled datasets according to cycle length, with darker shading indicating overlapping points.

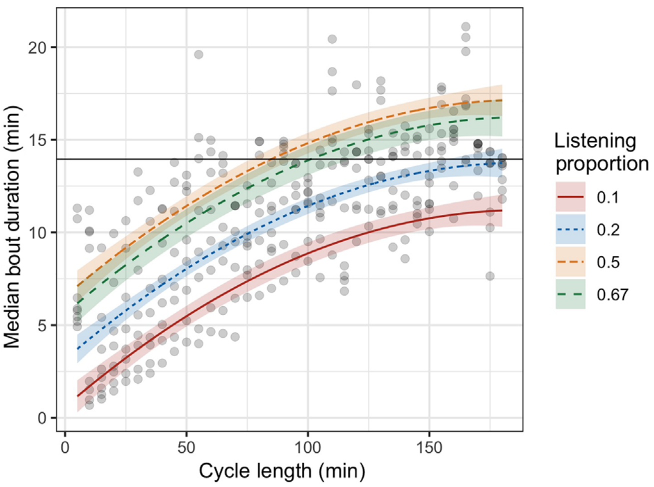

FIG. 3. (Color online) Median bout duration from subsampled datasets according to cycle length of each dataset. Lines represent predicted median bout durations from linear regression model with selected listening proportions of 0.1, 0.2, 0.5, or 0.67. Shading around lines represents 95% confidence intervals. Horizontal line represents actual median bout duration calculated from continuous data (13.95 min). Circles represent actual median bout durations from each subsampled dataset according to cycle length, with darker shading indicating overlapping points.

In the subsampled datasets, a maximum bout duration equal to the maximum bout duration in the continuous dataset (242.2 min) was exclusively found in the dataset created with a cycle length of 20 min and a listening proportion of 0.67. Only 10 of the subsampled datasets had maximum bout durations of greater than 200 min, all of which had cycle lengths of 5–20 min and listening proportions greater than 0.167. For cycle lengths greater than 20 min, the maximum bout duration was strongly correlated with the length of recording time per cycle ($r = 0.96$).

The median bout durations in subsampled datasets were modeled with a non-linear regression. Both cycle length and listening proportion were significant predictors of median bout duration ($p < 0.001$). Higher listening proportions led to median bout durations similar to those found in the continuous data, while lower listening proportions underestimated the median bout duration. Short cycle lengths (<60 min) underestimated the median bout duration regardless of the listening proportion (Fig. 3).[1]

All subsampled datasets contained bouts that were classified as unknown. In the binomial GLM with a logit link function used to model the proportion of unknown bouts, cycle length and listening proportion were both significant predictors ($p < 0.001$). Longer cycle lengths led to smaller proportions of unknown bouts, regardless of listening proportion. Higher listening proportions also led to smaller proportions of unknown bouts at shorter cycle lengths, but the difference in the proportion of unknown bouts between listening proportions decreased as the cycle length increased (Fig. 4).[1]

IV. DISCUSSION

The purpose of this study was to investigate the impact of duty cycles on the detection of SRKW calls and whistles and to examine how this affects the analysis of questions related to their behavior and occurrence. The impact of duty cycles varied depending on the scale of the research question and thus, the data required for accurate results. For broad-scale questions, most subsampled datasets produced results similar to the continuous data. However, when finer scale data were necessary, the listening proportion and cycle length affected the accuracy of the results.

A. Daily presence

There was a high probability of correctly detecting SRKW daily presence for almost all duty cycles tested.

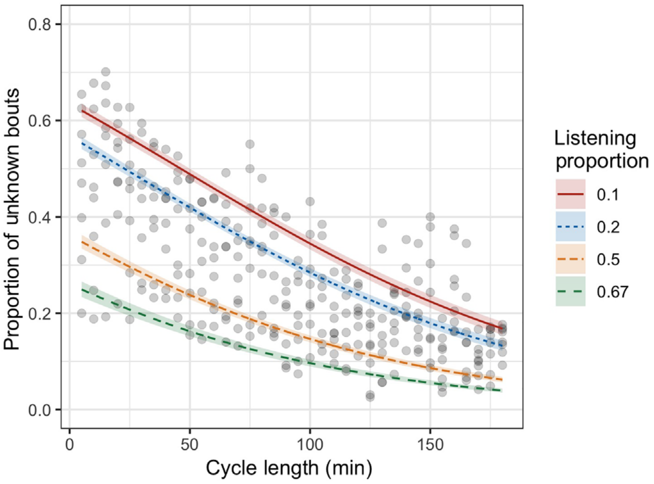

FIG. 4. (Color online) Proportion of bouts that could not be identified to ecotype in subsampled datasets according to cycle length. Lines represent predicted proportion of unknown bouts from binomial GLM with logit link function given a selected listening proportion of 0.1, 0.2, 0.5, or 0.67. Shaded areas around lines represent 95% confidence intervals. Circles represent actual proportion of unknown bouts by cycle length, with darker shading indicating overlapping points.

Cycle lengths between 5 min and 1 h had high probabilities of correct detection, regardless of the listening proportion. At cycle lengths greater than 1 h, daily presence was underestimated by 20%–40% at listening proportions between 0.1 and 0.4 (Fig. 1). Similar trends were also found in a study of the detection of the daily presence of several beaked whale species using subsampled data (Stanistreet *et al.*, 2016). These results suggest that cycle lengths as short as 5 min can be optimal for long-term acoustic studies of the daily presence of SRKW because they would allow the use of smaller listening proportions, limiting the overall recording time, while still maintaining a high probability of correct detection. For example, recording with a 15 min cycle length and a listening proportion of 0.2 would lead to 4.8 h of recordings per day, while recording with a 70 min cycle length and a listening porportion of 0.5 would lead to 12 h of recordings per day. Yet, both duty cycles would lead to similar probabilties of correctly detecting daily presence of SRKW.

The optimal duty cycle for the correct detection of daily presence in other species, however, may depend on the behavior of the species of interest. Thomisch *et al.* (2015) found trends in the probability of correct detection of daily presence of blue whales (*Balaenoptera musculus*) that are similar to those reported here, but the optimal cycle lengths were longer, between 1 and 6 h. These differences are likely attributable to the differences in acoustic behaviour between these two species. Blue whales produce sounds between 10 and 20 Hz (Rivers, 1997) which, because of the slower attenuation rate of low-frequency sounds (Wilcock *et al.*, 2014), allows them to be detected from distances of more than 500 km (Watkins *et al.*, 2000), while killer whales have been found to have a maximum detection range of about 4.3 km (Rankin *et al.*, 2008). As a result, blue whales have the potential to be in range of the hydrophone for much longer than killer whales. Furthermore, Antarctic blue whale song is made up of longer signals (18 s) than SRKW stereotyped calls, and these long signals are repeated in sequences with intercall intervals of around 60 s (Širović *et al.*, 2004), which would increase the likelihood of detecting daily presence of blue whales over a longer time frame. Therefore, while the trends in this study may be used as a starting point, the optimal duty cycle for detecting daily presence, or any of the patterns described here, will depend on the acoustic characteristics and behavior of the species of interest as well as factors that affect sound propogation.

B. Diel patterns

While duty cycles appear to have little effect on detections of daily presence, they have a greater effect when fine-scale data are required. Despite the lack of diurnal variation in SRKW hourly calling behavior in the continuous data, significant differences were found among light regimes in 13 of the subsampled datasets. Most of these datasets had cycle lengths greater than 1 h and listening proportions of less than 0.5. This suggests that in order to correctly identify diel patterns in SRKW hourly calling rates, cycle lengths between 5 min and 1 h and long listening proportions (> 0.5) are required. If a strong diurnal variation in SRKW calling behavior had been identified in the continuous data, duty cycling might have had a greater effect. Thomisch *et al.* (2015) found low probabilities of correctly calculating calling rates within 10% or 50% of the true calling rate from duty-cycled datasets when there was a distinct diel pattern in the continuous dataset.

C. Bouts

Using subsampled data affected the detection and identification of SRKW acoustic bouts. For a given cycle length, smaller listening proportions led to subsampled datasets with a greater total number of bouts and bouts with shorter durations when compared to the continuous data. The same trend was found as the cycle length decreased for a given listening proportion (Figs. 2 and 3). These results are consistent with the effect of duty cycles on the detection of killer whale acoustic encounters found by Riera *et al.* (2013), who found a greater number of total encounters and shorter encounter durations when they used a shorter listening proportion (0.33), though they only tested a cycle length of 30 min.

The extent to which subsampled datasets over- or underestimate the number and duration of bouts is related to the acoustic behavior of the species, and particularly to the actual duration of bouts. Duty cycles that provided the most accurate total number of bouts and median bout durations had cycle lengths between 35 and 165 min and most had a listening proportion of 0.5 or 0.67 (Figs. 2 and 3). Because the median bout duration in this dataset was 13.9 min, the combination of long cycle lengths and long listening proportions provided recording periods that were most likely to capture the entirety of an SRKW bout. In contrast, duty cycle settings (combinations of duty cycle lengths and listening proportions) that increase the likelihood that an entire bout would fit within the gap between recordings would increase the chances that bouts would be missed and total number of bouts would be underestimated. Furthermore, for all cycle lengths greater than 20 min, the maximum SRKW bout duration was underestimated which would lead to an underestimate of the variability in bout durations.

The effect of duty cycles on the detection of SRKW acoustic bouts also depended on the BCI. When the combination of duty cycle length and listening proportion resulted in recording gaps that were approximately equal to or less than the BCI (9.48 min), the number of bouts was overestimated. For example, the highest number of bouts were calculated for duty cycle lengths of 15 min and 20 min. In a duty cycle with a 15 min cycle length and a 0.33 listening proportion, there is a 10 min gap between successive recording times. At this duty cycle, every recording period with acoustic signals in it was classified as its own bout, splitting each long bout into many short bouts. Additionally, subsampled datasets with cycle lengths greater than 20 min and listening proportions of less than 0.167 underestimated the maximum bout duration because the gap between recording periods was greater than the BCI. This highlights the benefit of understanding a species' acoustic behavior before deciding on a duty cycling regime.

In addition to affecting the duration and number of bouts detected, duty cycling limited the number of bouts that could be identified to ecotype. The proportion of unidentified bouts decreased as cycle lengths increased or as the listening proportion increased (Fig. 4). These results are consistent with Riera *et al.* (2013) who found that there were a higher number of unidentified encounters in subsampled datasets with a 0.33 listening proportion than datasets with a 0.67 listening proportion. Identifying bouts is particularly important in studies of killer whales in the northeastern Pacific, where ecotypes overlap in habitat use but have different management priorities. The inability to identify SRKW bouts to ecotype may lead to the underestimation of their presence in the region which could affect designations of critical habitat that are essential for the recovery of this population.

Unlike hourly or daily patterns, the level of fine-scale data needed to understand bouts of SRKW acoustic behavior requires duty cycles with cycle lengths greater than 30 min. Additionally, a listening proportion of 0.5 or greater is required for results to be similar to those found in continuous data. When selecting a duty cycle to study SRKW acoustic bouts, researchers must balance the need for long study durations with the need to accurately identify the bouts to ecotype and to reflect the variation in bout durations. In other species, such as common dolphins (*Delphinus* spp.) and spinner dolphins (*Stenella longirostris*), species identification can depend on other acoustic features such as the proportion of particular whistle types in a recording (Gruden *et al.*, 2016; Oswald *et al.*, 2021) rather than the occurrence of species or ecotype-specific call types. Even when species identification is based on general characteristics of calls, it is necessary to capture representative samples of the vocal repertoires of the species in question (Rankin *et al.*, 2017). It is likely that successful species identification in other species would need long listening proportions and would require similar tradeoffs between long study durations and accurate information about acoustic bouts, but exact thresholds need to be determined empirically for different species.

D. Applications in other habitats, populations, and species

The trends found in this study can be used to predict how passive acoustic studies of other species may be impacted by specific duty cycles. For instance, fin whale (*Balaenoptera physalus)* song occurs in bouts with a BCI of 35 min (Clark *et al.*, 2019). If recorded with a duty cycle, the overestimation of the total number of bouts of fin whale song would not occur until the gaps between recording periods of each cycle exceeded 35 min.

While the general trends in the effects of duty cycle characteristics may be applicable to other species, populations, or habitats, the numerical results presented here are likely to be specific to SRKW in Haro Strait during the time of the study. Bout durations may vary with habitat use and behavior of the individuals in the study area, as well as with the detection range of the hydrophone. The amplitude and frequency ranges of sounds produced by the species of interest, the directionality of those sounds, environmental factors, and the sensitivity of the hydrophone can all affect the distance from the hydrophone at which a species can be detected and recorded (Zimmer, 2011). Therefore, bout durations may differ depending on the detection range of the species of interest.

Additionally, the use of an automated detector (PAMGuard WMD) to analyze the continuous acoustic recordings may have influenced the results. Automatic detectors can both miss target signals (missed detections) and detect signals that are not target signals (false detections). In this analysis, the goal was to minimize missed detections and so WMD settings were selected that produced a high number of false detections (42% of detections in the entire study period were false detections). These settings were likely to detect most SRKW calls and whistles in the data and a small number of missed detections would be unlikely to have a significant impact on the results.

E. Conclusions

This study provides a framework for a quantitative assessment of the optimal duty cycles for research in marine acoustics. The framework developed here can be used to guide the selection of optimal duty cycles and to understand the effects of duty cycles on the analysis of acoustic recordings of cetaceans. For example, for many questions, the optimal duty cycle to study SRKW occurrence and behavior had short cycle lengths (between 5 min and 1 h), which facilitated the capture of variation in acoustic behavior throughout the day. This appears to be true across several marine mammal taxa, as similar patterns were found in studies of blue and North Atlantic right whales (Thomisch *et al.*, 2015) and beaked whales (Stanistreet *et al.*, 2016). The definition of short cycle length, however, varies with the acoustic behavior of the species of interest. This may make it difficult to select an optimal duty cycle for species whose acoustic behavior is unknown. Furthermore, when fine-scale acoustic data are needed, the optimal duty cycle greatly depends on the acoustic characteristics and behavior of the species of interest in the study area. This could limit the ability to use the same subsampled datasets to assess both broad- and fine-scale questions for a given species as well as across multiple species. Therefore, when addressing research questions about fine-scale acoustic behavior, a preliminary study using continuous data should be conducted to assess the optimal duty cycle for that species in the study area. These recommendations also apply when considering subsampling of continuous recordings, such as those made with animal-borne tags (Silva *et al.*, 2016) or towed hydrophone arrays (Rankin *et al.*, 2008). Using duty cycles when recording passive acoustic data provides advantages in terms of allowing longer-term data collection and reducing the volume of data collected and analyzed; however, care must be taken when choosing duty cycle regimes. The choice of duty cycle can have a significant impact on the results of analyses and the same duty cycle will not be best suited for all species and situations.

ACKNOWLEDGMENTS

We are grateful to Colleen Reichmuth and two anonymous reviewers for their suggestions, which have improved the quality of the manuscript. We thank Will Cresswell for his feedback and insight on the statistical models used in this analysis. We also thank Vincent Janik for his mentorship and feedback. Data were collected in collaboration with The Whale Museum and with permission of Washington State Parks and the U. S. Coast Guard with funding from the ECHO Program of the Vancouver Fraser Port Authority.

[1] See supplementary material at https://www.scitation.org/doi/suppl/10.1121/10.0009752 for model parameter estimates, standard errors, and measures of model fit.

Au, W. W. L., Giorli, G., Chen, J., Copeland, A., Lammers, M., Richlen, M., Jarvis, S., Morrissey, R., Moretti, D., and Klinck, H. (**2013**). “Nighttime foraging by deep diving echolocating odontocetes off the Hawaiian islands of Kauai and Ni’ihau as determined by passive acoustic monitors,” J. Acoust. Soc. Am. **133**, 3119–3127.

Bates, D., Machler, M., Bolker, B., and Walker, S. (**2015**). “Fitting linear mixed-effects models using lme4,” J. Stat. Softw. **67**, 1–48.

Center for Conservation Bioacoustics (**2019**). “Raven Pro: Interactive Sound Analysis Software.”

Clark, C. W., Gagnon, G. J., and Frankel, A. S. (**2019**). “Fin whale singing decreases with increased swimming speed,” R. Soc. Open Sci. **6**, 180525.

Deecke, V. B., Ford, J. K. B., and Slater, P. J. B. (**2005**). “The vocal behaviour of mammal-eating killer whales: Communicating with costly calls,” Anim. Behav. **69**, 395–405.

Diogou, N., Klinck, H., Frantzis, A., Nystuen, J., Papthanassiou, E., and Katsanevakis, S. (**2019**). “Year-round acoustic presence of sperm whales (Physeter macrocephalus) and baseline ambient sound levels in the Greek Seas,” Mediterr. Mar. Sci. **20**, 208–221.

Emmons, C. K., Bradley Hanson, M., and Lammers, M. O. (**2021**). “Passive acoustic monitoring reveals spatiotemporal segregation of two fish-eating killer whale *Orcinus orca* populations in proposed critical habitat,” Endanger. Species Res. **44**, 253–261.

Ford, J. K. B. (**1987**). *A Catalogue of Underwater Calls Produced by Killer Whales (Orcinus orca) in British Columbia* (Department of Fisheries and Oceans, Nanaimo), p. 165.

Ford, J. K. B. (**1991**). “Vocal traditions among resident killer whales (*Orcinus orca*) in coastal waters of British Columbia,” Can. J. Zool. **69**, 1454–1483.

Gillespie, D., Mellinger, D. K., Gordon, J., McLaren, D., Redmond, P., McHugh, R., Trinder, P., Deng, X., and Thode, A. (**2009**). “PAMGUARD: Semiautomated, open source software for real-time acoustic detection and localization of cetaceans,” J. Acoust. Soc. Am. **125**, 2547.

Gruden, P., White, P. R., Oswald, J. N., Barkley, Y., Cerchio, S., Lammers, M., and Baumann-Pickering, S. (**2016**). “Differences in oscillatory whistles produced by spinner (*Stenella longirostris*) and pantropical spotted (*Stenella attenuata*) dolphins,” Mar. Mammal Sci. **32**, 520–534.

Hannay, D. E., Delarue, J., Mouy, X., Martin, B. S., Leary, D., Oswald, J. N., and Vallarta, J. (**2013**). “Marine mammal acoustic detections in the northeastern Chukchi Sea, September 2007–July 2011,” Cont. Shelf Res. **67**, 127–146.

Hanson, M. B., Emmons, C. K., Ward, E. J., Nystuen, J. A., and Lammers, M. O. (**2013**). “Assessing the coastal occurrence of endangered killer whales using autonomous passive acoustic recorders,” J. Acoust. Soc. Am. **134**, 3486–3495.

Janik, V. M., King, S. L., Sayigh, L. S., and Wells, R. S. (**2013**). “Identifying signature whistles from recordings of groups of unrestrained bottlenose dolphins (*Tursiops truncatus*),” Mar. Mammal Sci. **29**, 109–122.

Lammers, M. O., Howe, M., Zang, E., McElligott, M., Engelhaupt, A., and Munger, L. (**2017**). “Acoustic monitoring of coastal dolphins and their response to naval mine neutralization exercises,” R. Soc. Open Sci. **4**, 170558.

Lammers, M. O., and Oswald, J. N. (**2015**). “Analyzing the acoustic communication of dolphins,” in *Dolphin Communication and Cognition: Past, Present, and Future*, edited by D. L. Herzing and C. M. Johnson (MIT Press, Cambridge) pp. 107–138.

Martin, P., and Bateson, P. (**2017**). *Measuring Behaviour*, 3rd ed. (Cambridge University Press, Cambridge, UK), pp.121–134.

Miller, P. J. O., Shapiro, A. D., Tyack, P. L., and Solow, A. R. (**2004**). “Call-type matching in vocal exchanges of free-ranging resident killer whales, *Orcinus orca*,” Anim. Behav. **67**, 1099–1107.

Oswald, J. N., Au, W. W. L., and Duennebier, F. (**2011**). “Minke whale (*Balaenoptera acutorostrata*) boings detected at the Station ALOHA Cabled Observatory,” J. Acoust. Soc. Am. **129**, 3353–3360.

Oswald, J. N., Ou, H., Au, W. W. L., Howe, B. M., and Duennebier, F. (**2016**). “Listening for whales at the station ALOHA cabled observatory,” in *Listening in the Ocean* (Springer, New York), pp. 221–237.

Oswald, J. N., Walmsley, S. F., Casey, C., Fregosi, S., Southall, B., and Janik, V. M. (**2021**). “Species information in whistle frequency modulation patterns of common dolphins,” Philos. Trans. R. Soc. B **376**, 20210046.

Parks, S. E., and Clark, C. W. (**2008**). “Acoustic communication in mysticetes,” Bioacoustics **17**, 45–47.

Rankin, S., Archer, F., Keating, J., Oswald, J. N., Oswald, M., Curtis, A., and Barlow, J. (**2017**). “Acoustic classification of dolphins in the California Current using whistles, echolocation clicks, and burst pulses,” Mar. Mammal Sci. **33**, 520–540.

Rankin, S., Oswald, J. N., and Barlow, J. (**2008**). “Acoustic behavior of dolphins in the Pacific Ocean: Implications for using passive acoustic methods for population studies,” Can. J. Acoust. **36**, 88–92.

R Core Team (**2021**). “R: A language and environment for statistical computing.”

Rekdahl, M. L., Dunlop, R. A., Goldizen, A. W., Garland, E. C., Biassoni, N., Miller, P., and Noad, M. J. (**2015**). “Non-song social call bouts of migrating humpback whales,” J. Acoust. Soc. Am. **137**, 3042–3053.

Rice, A., Deecke, V., Ford, J., Pilkington, J., Oleson, E., Hildebrand, J., and Širović, A. (**2017**). “Spatial and temporal occurrence of killer whale ecotypes off the outer coast of Washington State, USA,” Mar. Ecol. Prog. Ser. **572**, 255–268.

Richard, G., Filatova, O. A., Samarra, F. I. P., Fedutin, I. D., Lammers, M., and Miller, P. J. (**2017**). “Icelandic herring-eating killer whales feed at night,” Mar. Biol. **164**, 32.

Richardson, J. W., Greene, C. R., Malme, C. I., and Thompson, D. H. (**1995**). *Marine Mammals and Noise* (Academic Press, San Diego), p. 576.

Riera, A., Ford, J. K., and Ross Chapman, N. (**2013**). “Effects of different analysis techniques and recording duty cycles on passive acoustic monitoring of killer whales,” J. Acoust. Soc. Am. **134**, 2393–2404.

Riera, A., Pilkington, J., Ford, J., Stredulinsky, E., and Chapman, N. (**2019**). “Passive acoustic monitoring off Vancouver Island reveals extensive use by at-risk Resident killer whale (*Orcinus orca*) populations,” Endanger. Species Res. **39**, 221–234.

Riesch, R., Ford, J. K. B., and Thomsen, F. (**2006**). “Stability and group specificity of stereotyped whistles in resident killer whales, *Orcinus orca*, off British Columbia,” Anim. Behav. **71**, 79–91.

Rivers, J. A. (**1997**). “Blue whale, *Balaenoptera musculus*, vocalizations from the waters off central California,” Mar. Mammal Sci. **13**, 186–195.

Samarra, F. I. P., Deecke, V. B., Vinding, K., Rasmussen, M. H., Swift, R. J., and Miller, P. J. O. (**2010**). “Killer whales (*Orcinus orca*) produce ultrasonic whistles,” J. Acoust. Soc. Am. **128**, EL205–EL210.

Silva, T. L., Mooney, T. A., Sayigh, L. S., Tyack, P. L., Baird, R. W., and Oswald, J. N. (**2016**). “Whistle characteristics and daytime dive behavior in pantropical spotted dolphins (*Stenella attenuata*) in Hawai’i measured using digital acoustic recording tags (DTAGs),” J. Acoust. Soc. Am. **140**, 421–429.

Širović, A., Hildebrand, J. A., Wiggins, S. M., McDonald, M. A., Moore, S. E., and Thiele, D. (**2004**). “Seasonality of blue and fin whale calls and the influence of sea ice in the Western Antarctic Peninsula," Deep. Res. Part II **51**, 2327–2344.

Širović, A., Hildebrand, J. A., Wiggins, S. M., and Thiele, D. (**2009**). "Blue and fin whale acoustic presence around Antarctica during 2003 and 2004," Mar. Mammal Sci. **25**, 125–136.

Slater, P. J. B., and Lester, N. P. (**1982**). "Minimising errors in splitting behaviour into bouts," Behaviour **79**, 153–161.

Sousa-Lima, R. S., Norris, T. F., Oswald, J. N., and Fernandes, D. P. (**2013**). "A review and inventory of fixed autonomous recorders for passive acoustic monitoring of marine mammals," Aquat. Mamm. **39**, 23–53.

Stafford, K. M., Moore, S. E., and Fox, C. G. (**2005**). "Diel variation in blue whale calls recorded in the eastern tropical Pacific," Anim. Behav. **69**, 951–958.

Stanistreet, J. E., Nowacek, D. P., Read, A. J., Baumann-Pickering, S., Moors-Murphy, H. B., and Van Parijs, S. M. (**2016**). "Effects of duty-cycled passive acoustic recordings on detecting the presence of beaked whales in the northwest Atlantic," J. Acoust. Soc. Am. **140**, EL31–EL37.

Thomisch, K., Boebel, O., Zitterbart, D. P., Samaran, F., Van Parijs, S., and Van Opzeeland, I. (**2015**). "Effects of subsampling of passive acoustic recordings on acoustic metrics," J. Acoust. Soc. Am. **138**, 267–278.

United States Naval Observatory (**2019**). https://www.usno.navy.mil/USNO/astronomical-applications (Last viewed June 1, 2020).

Van Opzeeland, I., Van Parijs, S., Bornemann, H., Frickenhaus, S., Kindermann, L., Klinck, H., Plötz, J., and Boebel, O. (**2010**). "Acoustic ecology of antarctic pinnipeds," Mar. Ecol. Prog. Ser. **414**, 267–291.

Van Parijs, S. M., Clark, C. W., Sousa-Lima, R. S., Parks, S. E., Rankin, S., Risch, D., and Van Opzeeland, I. C. (**2009**). "Management and research applications of real-time and archival passive acoustic sensors over varying temporal and spatial scales," Mar. Ecol. Prog. Ser. **395**, 21–36.

Veirs, S., Veirs, V., and Wood, J. D. (**2016**). "Ship noise extends to frequencies used for echolocation by endangered killer whales," PeerJ **4**, e1657.

Venables, W. N., and Ripley, B. D. (**2002**). *Modern Applied Statistics with S*, 4th ed. (Springer, New York).

Watkins, W. A., Daher, M. A., Reppucci, G. M., George, J. E., Martin, D. L., DiMarzio, N. A., and Gannon, D. P. (**2000**). "Seasonality and distribution of whale calls in the North Pacific," Oceanography **13**, 62–67.

Wilcock, W. S. D., Stafford, K. M., Andrew, R. K., and Odom, R. I. (**2014**). "Sounds in the ocean at 1–100 Hz," Ann. Rev. Mar. Sci. **6**, 117–140.

Zimmer, W. (**2011**). *Passive Acoustic Monitoring of Cetaceans* (Cambridge University Press, Cambridge), pp. 356.