

Repertoire and classification of non-song calls in Southeast Alaskan humpback whales (*Megaptera novaeangliae*)

Michelle E. Fournet^{a)}

College of Earth Ocean and Atmospheric Sciences, Oregon State University, 104 CEOAS Administration Building, Corvallis, Oregon 97333

Andy Szabo

Alaska Whale Foundation, P.O. Box 1927, Petersburg, Alaska 99833

David K. Mellinger^{b)}

Cooperative Institute for Marine Resources Studies, Oregon State University, 2030 SE Marine Science Drive, Newport, Oregon 97365

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On low-latitude breeding grounds, humpback whales produce complex and highly stereotyped songs as well as a range of non-song sounds associated with breeding behaviors. While on their Southeast Alaskan foraging grounds, humpback whales produce a range of previously unclassified non-song vocalizations. This study investigates the vocal repertoire of Southeast Alaskan humpback whales from a sample of 299 non-song vocalizations collected over a 3-month period on foraging grounds in Frederick Sound, Southeast Alaska. Three classification systems were used, including aural spectrogram analysis, statistical cluster analysis, and discriminant function analysis, to describe and classify vocalizations. A hierarchical acoustic structure was identified; vocalizations were classified into 16 individual call types nested within four vocal classes. The combined classification method shows promise for identifying variability in call stereotypy between vocal groupings and is recommended for future classification of broad vocal repertoires.

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I. INTRODUCTION

In recent years, efforts to use acoustical research methods to study marine mammals have intensified. Species' vocalizations have been used to investigate population structure in several cetaceans, including blue whales (*Balaenoptera musculus*; McDonald *et al.*, 2006), fin whales (*B. physalus*; Castellote *et al.*, 2011), common minke whales (*B. acutorostrata*; Mellinger *et al.*, 2000; Gedamke *et al.*, 2001), and killer whales (*Orcinus orca*; Ford, 1991). Estimating marine mammal abundance and density using acoustics has been proposed as a cost-effective supplement to traditional ship-based visual surveys (Mellinger and Barlow, 2003). Additionally, the use of acoustic data is essential for studying vocal communication in marine mammals, and acoustic data collected in its current state may be an importance reference against which to assess species' resilience to changes in the marine soundscape. Interpretation of acoustic data, however, is often contingent on understanding a species' vocal repertoire.

The vocal repertoire of humpback whales (*Megaptera novaeangliae*) is broad and complex. While on low-latitude breeding grounds, humpback whales produce highly stereotyped songs that are directly or indirectly related to mating

behaviors (Payne and McVay, 1971; Au *et al.*, 2006). Humpbacks also produce a second class of sounds across their geographic range known as “non-song vocalizations.” Silber (1986) used the term “social sounds” to describe any non-song vocalization “that does not possess the rhythmic and continuous patterning of song.” This includes single song units produced independently of the song structure (“song unit social sounds”; Dunlop *et al.*, 2007; Rekdahl *et al.*, 2013), novel vocalizations not present in song units (Dunlop *et al.*, 2007; Dunlop *et al.*, 2008; Rekdahl *et al.*, 2013), and surface-generated sounds (Tyack, 1983; Dunlop *et al.*, 2007).

The first detailed description of non-song vocalizations used an aural-visual analysis and various multivariate analysis techniques to describe 34 discrete vocal types in migrating humpbacks in eastern Australia (Dunlop *et al.*, 2007). Rekdahl *et al.* (2013) later expanded the regional repertoire to a total of 46 vocal types. However, data was collected occurred along a migratory corridor and may not be indicative of vocal behavior on foraging grounds or in other ocean basins. A similar approach by Stimpert *et al.* (2011) used a cluster analysis to separate humpback vocalizations from a North Atlantic foraging ground into eight groups with similar acoustic properties. While quantitative descriptions of the resultant groupings were reported, only two vocal types were uniquely described. The study benefited from increased objectivity, however, because of the methodology, the broad results limit comparison of vocalizations from different regions.

^{a)}Author to whom correspondence should be addressed. Electronic mail: michelle.fournet@gmail.com

^{b)}Also at NOAA Pacific Marine Environmental Laboratory, 2030 SE Marine Science Drive, Newport, Oregon 97365.

Comparatively little research has been done on foraging humpback populations in the North Pacific. Broad acoustic parameters of non-song vocalizations were reported for Southeast Alaskan humpback whales, but no effort was made to systematically distinguish one call type from another or to generate a catalog of unique call types (Thompson *et al.*, 1986). A highly stereotyped sound dubbed a “feeding call” has been well described by D’Vincent *et al.* (1985), Sharpe (2001), and Cerchio and Dalheim (2001), but was notably absent from the report of Thompson *et al.* indicating that this description of non-song vocalizations from the area was not comprehensive. The Southeast Alaskan “Whup” call, whose acoustic properties and usage patterns were recently described in Glacier Bay, Southeast Alaska (Wild and Gabriele, 2014), is the only other call type to be the subject of focused research. With these two exceptions, the known repertoire of non-song vocalizations from the North Pacific population of humpback whales is poorly described, making it unsuitable for PAM, comparisons to other populations or as the basis for investigating call function or stability. While efforts to describe non-song vocalizations have intensified, few humpback populations have been adequately surveyed and few methodologies employed that classify non-song vocalizations with a high degree of detail. That humpback whales produce a diverse array of sounds suggests that communication between conspecifics is an important aspect of humpback behavior. Understanding the role of humpback whale non-song vocalizations will benefit from developing vocalization catalogs that can be compared between different social and behavioral contexts (breeding, migrating, foraging) and populations. The goal of this study is to develop a catalogue of non-song vocalizations produced by humpback whales from a Southeast Alaskan foraging ground. We quantify the acoustic parameters of these vocalizations and use a combination of classification methods employed by earlier researchers, yet previously uncombined, to study marine mammal vocalizations. Specifically, we use a three-part classification method that includes (1) aural-visual (AV) analysis, (2) statistical cluster analysis, and (3) discriminant function analysis (DFA). In doing so, we present a standardized and increasingly objective methodology for classifying vocalizations that will permit comparisons between vocalization catalogs developed for other populations or other species. Further, this study will expand the known vocal repertoire for humpback whales on their foraging grounds and for the species as a whole. For the purpose of this study, the term “call” or “non-song vocalization” refers to any vocalization produced in a non-song context and excludes surface-generated percussive sounds.

II. METHODS

Acoustic data were collected from June–September 2012 in the waters of Frederick Sound, Southeast Alaska, within a 1 nautical mile radius of the Five Finger Lighthouse (57° 16′ 13″ N, 133° 37′ 53″ W; Fig. 1). Acoustic recordings were made via two omnidirectional hydrophones (Cetacean Research Technology C-55), each with a built in +20 dB preamplifier, an effective sensitivity of –165 dB, and a flat

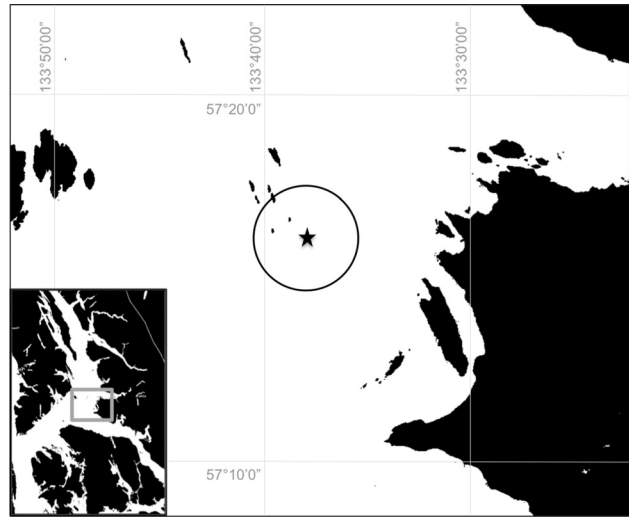


FIG. 1. Map showing survey area in Frederick Sound, SE Alaska, including the location of the research station at the Five Finger Lighthouse (starred).

frequency response (± 3 dB) from 10 Hz to 10 kHz. The hydrophones were connected to a digital audio recorder (H4N Zoom Handy) operated with a 44.1 kHz sampling rate and 16-bit sample resolution. Hydrophones were separated by 4.5 m (or 3.3 m when ocean surface conditions necessitated) and deployed to a depth of 20–25 m from the port and starboard side of a 3 m inflatable vessel. Five-pound weights were attached to each hydrophone to facilitate sinking. All recordings were obtained when the vessel was adrift with the engine off. No other baleen whale species were seen in the study area during the three months of study, and all vocalizations that fell within reasonable parameters for baleen whale vocalizations were assumed to be produced by humpbacks.

A. Data processing and analysis

Spectrograms of recordings were generated using RavenPro 1.4 (Cornell Laboratory of Ornithology) with a 4096-point Fast Fourier Transform (FFT), Hann window (providing 42.7 Hz resolution) and 75% overlap, and the MATLAB-based program Osprey (Mellinger, 2014) with the same parameters except a Hamming window. Recordings were manually reviewed in their entirety and samples were extracted using RavenPro. The signal-to-noise ratio (SNR) of each extracted sample—the level of the sample above background noise—was calculated using the method described by Mellinger and Bradbury (2007). To be included in the analysis, humpback whale vocalizations had to have a SNR of 10 dB or higher (Dunlop *et al.*, 2007; Dunlop *et al.*, 2008; Stimpert *et al.*, 2011; Rekdahl *et al.*, 2013) and have visually and aurally distinguishable start and end points to ensure accurate parameter measurements. Consistent with Dunlop *et al.* (2007), Stimpert *et al.* (2011), and Rekdahl *et al.* (2013), call parameters relating to both frequency and time were measured and extracted from spectrogram samples for statistical analyses (Table I).

In addition to traditional acoustic measurements, we selected parameters from a pre-programmed Noise-Resistant Feature Set (NRFS; Mellinger and Bradbury, 2007) within

TABLE I. Description of acoustic variables used for analysis for three-part classification of humpback whale social calls.

Measurement	Notation	Description
Duration (s) ^a	Dur	Length of feature box
Vocalizations per Bout	Bout	Number of repetitions of the same unit of sound within a single calling event (“Bout”)
Lower Frequency (Hz) ^{a,b}	Low	Lowest frequency limits of feature box
Upper Frequency (Hz) ^{a,b}	Max	Highest frequency limit of feature box
Start Frequency (Hz) ^b	Start F ₀	The fundamental frequency at the start of the call
End Frequency (Hz) ^b	End F ₀	The fundamental frequency at the end of the call
Peak Frequency (Hz) ^b	Peak	Frequency of the spectral peak
Bandwidth (Hz) ^{a,b}	Band	Height of feature box
Median Frequency (Hz) ^{a,b}	MedF	Frequency where cumulative sum of cell values reach 50% of the total energy
Frequency Quartile (Hz) ^{a,b}	FreqQ	Frequency where cumulative sum of energies is 25% of total energy in Feature Box
Amplitude Modulation Rate ^a	AM Rate	Dominant rate of Amplitude Modulation
Frequency Modulation Rate ^a	FM Rate	Dominant rate of frequency modulation
Upsweep Fraction ^a	UpFrac	Fraction of time in which median frequency in one block is greater than that in preceding block, weighted by total energy in each block
Frequency Trend ^b	FreqTrend	Start F ₀ / End F ₀
Aggregate Entropy	Entropy	A measure of total disorder in the call

^aFeature from the Noise Resistant Feature Set (NRFS).

^bVariables that were log-transformed for analysis (see text).

the MATLAB-based program Osprey (Mellinger, 2014). NRFS was designed for detection and classification of marine animal sounds in noisy environments. Based on Fristrup and Watkins’ (1993) “Acoustat” approach, NRFS includes robust methods for assessing a number of salient acoustic features. In lieu of taking measurements from an observer-drawn annotation box, when using the NRFS a smaller time-frequency region, known as the feature box, is de-noised and calculated based on an algorithm that ranks summed energy within the sound relative to background noise. In this manner the louder parts of the spectrogram, which remain evident in high-noise situations, have the strongest influence on the calculated feature values (Mellinger and Bradbury, 2007). These features correspond to more traditional acoustical measurements but have the additional benefit of being more robust to variable noise conditions and sound attenuation. This was particularly important for this study, given that hydrophones were cabled to a drifting vessel, subject to flow and vessel noise, and affected by variable environmental conditions.

B. Vocal classification and statistical analysis

Three separate analyses were conducted to classify vocalizations: Aural-Visual (AV) classification by a human observer, hierarchical agglomerative cluster analysis, and discriminant function analysis (DFA). Sample files were stripped of identifying information and randomly ordered for the AV analysis. Samples were visually inspected in Raven Pro 1.4 by a single observer (MF) while simultaneously listening to the sample. Initially, samples were broadly grouped based on visual and acoustic similarities. Samples within the resulting groups were then re-randomized and subsequently sorted into smaller sub-groups. This process was repeated until the observer (MF) judged that calls were of the same call type. Neither the classification structure nor the number of groups or sub-groups was pre-determined. To account for possible outliers and individual variation, only vocalizations

that were present on a minimum of two non-consecutive sampling days were included in the final results.

Several acoustic parameters used in the analysis (Table I) were log-transformed, to minimize skew and to better approximate the mammalian perception of pitch (Richardson *et al.*, 1995; Parks and Tyack, 2005; Dunlop *et al.*, 2008; Stimpert *et al.*, 2011). These parameters were used in a hierarchical agglomerative cluster analysis (JMP Pro 9) to generate unsupervised call groupings (clusters). A dendrogram was generated using a Ward’s distance linkage method and a conservative cutoff point on the resulting tree was determined based on distance values and information retained (Stimpert *et al.*, 2011; Chmelnitsky and Ferguson, 2012). The resultant clusters were compared to the results of the AV analysis to determine the level of agreement between the two methods. If all of the calls placed together in a single group through AV classification were also placed in a single cluster, then agreement was said to be 100% for that call group.

DFA with cross validation was used as a supervised method to determine the likelihood of vocalizations being correctly classified to each of the possible groups through the AV analysis. DFA has been used in studies classifying dolphin vocalizations (Boisseau, 2005), southern right whales (*Eubalaena australis*) (Clark, 1982), and humpback whale social sounds (Dunlop *et al.*, 2007). Supervised methods, including DFA, differ from the unsupervised clustering technique in that they use existing data as a training set and make predictions based upon the dataset as a whole. The same call parameters used in the cluster analysis were used to conduct the DFA. Pooled DFA, where a DFA is run on the total data set, was conducted to assess the total agreement between methods; within-group DFA, or a DFA run on the calls of a given vocal group, was used to assess classification agreement at finer scales. Acoustic parameters identified through AV analysis to characterize each grouping were tested using Wilcoxon Rank-Sum statistical analyses. Multiple comparisons were made using the non-parametric

Steel-Dwass method (non-parametric form of Tukey's Honest Significant Difference Test; [Hollander and Wolfe, 1999](#)).

Spectrograms in this study were visually compared with spectrograms from the published literature to compare calls between and within populations. Differences in recording equipment, filtering, and analysis techniques in combination with absent or limited sound files for comparison limit the scope of inference to identifying similarities; however, where ample sound recordings from the same populations were available for direct comparison (i.e., sound clips from Glacier Bay) AV analysis was used to compare vocalizations.

III. RESULTS

A total of 32 sampling days between June and September 2012 resulted in 92.6 h of recordings. From these, 299 samples of humpback whale vocalizations met the criteria for analysis. Acoustic parameters varied widely among vocalizations. Starting fundamental frequency ranged from 31 Hz to 3.24 kHz with an average of 277 Hz (± 398 Hz), and a mean peak frequency of 341 Hz (± 601 Hz). Call duration ranged from 0.2 to 100.7 s, averaging 3.5 s (± 10.3 s), with a median of 1.1 s. The 100.7 s vocalization, which was a statistical outlier, was a multi-unit feeding call; most calls ($n=293$) were under 15 s. Bandwidth for all calls ranged from 49 Hz to >10 Hz (beyond which the hydrophone sensitivity began to roll off) with a mean of 919 Hz (± 1572 Hz). The smallest identifiable unique units of sound, identified by AV classification, which were produced in isolation and separated from other sounds by silence greater than the duration of the sound itself, were defined as "call types." Sixteen call types were identified, nested within seven vocal subclasses, within four general vocal classes.

The hierarchical agglomerative cluster analysis identified four principal statistical clusters, which were chosen based on the amount of information retained by each sample

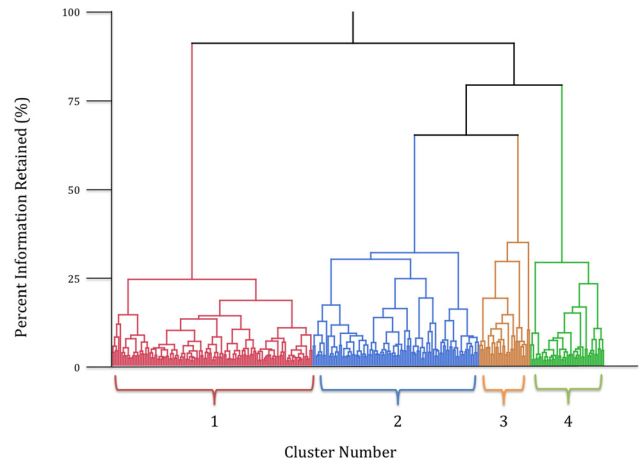


FIG. 2. Dendrogram showing results of an agglomerative hierarchical cluster analysis. Clusters representing the four call classes are identified numerically and with brackets (color online). Cluster 1 corresponds most directly with the low-frequency harmonic (LFH) vocal class. Cluster 2 corresponds most directly with the Tonal (T) vocal class. Cluster 3 corresponds most directly with the pulsed (P) vocal class. Cluster 4 corresponds most directly with the noisy/complex (NC) vocal class.

(~73%) and proportional distance between splits (Fig. 2). Each cluster corresponded with a high degree of overlap to one of the vocal classes identified by AV analysis, although no single vocal class was encompassed within a cluster (Table II). There was 83% agreement ($n=247$) between clusters and vocal classes (Tables II and III), meaning that 83% of all vocalizations determined by AV analyses to be of a single vocal class were grouped within the same cluster (i.e., AV analyses placed 82 vocalizations into a single vocal class; of these, 68 were grouped within a single cluster, so agreement for this vocal class is $68/82 \approx 83\%$). As for discriminant function analysis, when samples were pooled, DFA correctly assigned 90% ($n=269$) of samples into the same vocal class as determined through AV classification, 78% ($n=233$) of samples into the same vocal subclass as determined through AV classification, and 72% ($n=215$) of

TABLE II. Summary of select acoustic parameters for each group identified by hierarchical cluster analysis. Mean parameters are in bold; standard deviations are below and listed in italics. Class refers to most closely corresponding vocal class. Call Types refers to types of calls (as determined by aural-visual analyses) to be contained in each cluster.

Cluster	Class	Call Types	<i>n</i>	Dur (s)	Bout (n)	Start (Hz)	End (Hz)	Peak (Hz)	Cent. (Hz)	Lower (Hz)	Upper (Hz)	Band (Hz)	MedF (Hz)	AM	FM	Up
1	Low Freq. Harm.	Des. Moan, Des. Shriek, Mod. Harm.	122	1.0	1.0	89	93	114	159	71	276	205	129	1.9	1.9	-1.3
		Moan, Growl, Whup, Swop, Teepee		<i>1.4</i>	<i>0.4</i>	<i>38</i>	<i>34</i>	<i>45</i>	<i>24</i>	<i>97</i>	<i>91</i>	<i>47</i>	<i>1.9</i>	<i>1.4</i>	<i>2.5</i>	
2	Tonal	Feed, Ahooga	45	16.7	3.5	463	461	479	480	422	525	103	474	0.8	0.3	0.0
				<i>23.9</i>	<i>4.9</i>	<i>102</i>	<i>103</i>	<i>86</i>	<i>81</i>	<i>91</i>	<i>86</i>	<i>51</i>	<i>84</i>	<i>1.7</i>	<i>0.4</i>	<i>0.3</i>
3	Pulsed	Desc. Moan, Drop, Groan, Horse, Mod. Moan, Growl, Whup, Squeegie, Swop, Teepee, Var.	101	0.8	5.2	207	316	252	360	135	880	745	280	2.2	2.6	3.1
		Moan, Ahooga		<i>0.8</i>	<i>6.0</i>	<i>200</i>	<i>381</i>	<i>117</i>	<i>166</i>	<i>56</i>	<i>672</i>	<i>654</i>	<i>124</i>	<i>1.8</i>	<i>2.2</i>	<i>12.8</i>
4	Noisy	Asc. Shriek, Desc. Shriek, Horse, Squeegie, Swop, Trumpet, Var. Moan	31	1.6	1.3	999	1192	1307	1486	696	3459	2762	1269	2.1	1.5	0.1
				<i>1.0</i>	<i>1.0</i>	<i>732</i>	<i>1037</i>	<i>1335</i>	<i>1163</i>	<i>550</i>	<i>3689</i>	<i>3219</i>	<i>978</i>	<i>2.9</i>	<i>1.2</i>	<i>32.7</i>

samples into the same call type as determined by AV classification.

A. Description of vocalizations

The following results describe call classes, subclasses and types based on AV classification. Vocal classes and subclasses were named according to salient acoustic properties (Table I) and indicated in capital letters. Call types were qualitatively named; in an effort to maintain consistency between naming schemes, existing names were honored and are marked with an asterisk. When more than one name had been used, precedents from Southeast Alaskan studies were favored based on availability of sound files for direct aural-visual comparison, promoting consistency within a single population (C. Gabriele, personal communication).

1. Low-frequency harmonic calls

The low-frequency harmonic (LFH) vocal class was the class represented most in the study ($n=147$). There was 80% ($n=117$) overlap between samples placed in the LFH class by AV analysis and those grouped into cluster 1 (Table III). Within-class DFA predicted the same vocal subclass and call types as AV classification for 90% ($n=133$) and 73% ($n=108$) of samples, respectively. Samples placed in this class were characterized by low fundamental frequencies, with most of the energy concentrated below 500 Hz (Table IV, Fig. 3). Wilcoxon Rank-Sum tests indicated that the mean lower starting frequency ($p < 0.001$) and mean peak frequency ($p < 0.001$) varied significantly across vocal classes. Steel-Dwass *post hoc* tests indicated that samples in the LFH class had significantly lower starting frequency ($p < 0.001$) and peak frequency ($p < 0.001$) than samples in the remaining three vocal classes. The number of repeated units of sound contained in a single call was significantly lower in LFH calls than any other call class ($p < 0.001$), vocalizations were generally short and non-repeated (Table IV). Mean duration was significantly shorter than calls in the tonal (T) vocal class ($p < 0.001$).

The LFH class was divided into three subclasses: Trilled, complex, and simple (Table IV, Fig. 3). Trilled calls had noticeable rapid temporal structure, which exhibited more amplitude modulation than the other two subclasses, appeared “smeared” from reverberation, and had narrower bandwidth other subclasses (mean $253 \text{ Hz} \pm 233 \text{ Hz}$;

TABLE III. Confusion matrix showing overlap between aural-visual (AV) analysis classification and hierarchical agglomerative cluster classification. High values are shown in bold. Agreement (%) is calculated as the percentage of calls determined through AV classification to be in the same vocal class to be placed into a single statistical cluster.

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Total
LFH	$n = 117$ (80%)	$n = 1$ (<1%)	$n = 27$ (18%)	$n = 2$ (1%)	147
T	$n = 0$ (0%)	$n = 42$ (98%)	$n = 1$ (2%)	$n = 0$ (0%)	43
P	$n = 3$ (4%)	$n = 0$ (0%)	$n = 69$ (83%)	$n = 10$ (12%)	82
NC	$n = 2$ (7%)	$n = 2$ (4%)	$n = 4$ (15%)	$n = 19$ (70%)	27
Total	122	45	101	31	299

$p < 0.001$). Growls* (Wild and Gabriele, 2014) and whups* (Wild and Gabriele, 2014) composed the trilled subclass (Table IV, Fig. 3). Complex calls had organized harmonic structure and lacked a trilled temporal pattern; modulated moans* (Dunlop *et al.*, 2007) and descending moans composed the complex subclass (Table IV, Fig. 3). Simple calls had fewer harmonics and less noticeable frequency or amplitude modulation. Groans and variable moans composed the simple subclass (Table IV, Fig. 3).

2. Pulsed calls

The pulsed (P) vocal class was the second most-represented vocal class ($n=83$). There was 83% ($n=69$) overlap between samples placed in this vocal class and samples quantitatively grouped into cluster 2 (Table III). Within class DFA predictions agreed with AV classification for 83% of samples ($n=68$) at the vocal subclass level and 81% of samples ($n=67$) at the call type level. Call types in the P vocal class typically included short repeated units of sound within each vocalization with low fundamental frequencies (Table IV, Fig. 4). The mean number of repetitions in the P call class was significantly higher than in other vocal classes ($p < 0.001$), and mean duration was significantly shorter than calls in the T vocal class ($p < 0.0001$).

Samples in the P vocal class fell into one of two subclasses: Simple or complex (Table IV; Fig. 4). Complex calls in the P vocal class were characterized by more amplitude modulation and greater mean bandwidth (mean Band $979 \pm 1309 \text{ Hz}$) than samples in the simple subclass. Simple calls in the P vocal class were highly stereotyped, were more narrowband on average than samples in the complex subclass (mean Band = $667 \text{ Hz} \pm 744$), and lacked harmonics (Fig. 4). Four call types were classified in the P vocal class based on AV examination (Table IV; Fig. 4). Swops, teepees, and horses were all classified as complex P calls; drop-lets were the exclusive call in the simple subclass.

3. Tonal calls

The tonal (T) vocal class was the third most represented vocal class ($n=43$). There was 98% ($n=42$) overlap between samples subjectively placed in this vocal class and samples quantitatively grouped into cluster 4 (Table III). However, based on AV examination, only one call type, the feeding call* (Cerchio and Dalheim, 2001), was classified within the T vocal class; no subclasses were determined to be present within this vocal class (Table IV). With only a single identified call type, it did not make sense to calculate within-class DFA. Samples in the T vocal class were characterized by narrow bandwidths, low fundamental frequencies, and low aggregate entropy (Table IV, Fig. 5). There is evidence that the mean bandwidth of samples within this class is significantly narrower than in other call classes ($p < 0.0001$). There is also evidence that aggregate entropy was significantly lower in samples from the T vocal class than in other vocal classes ($p < 0.0001$). Feeding calls lacked harmonics or amplitude modulation and may occur in short bouts (Table IV, Fig. 5).

TABLE IV. Summary of select acoustic parameters for samples classified using aural-visual analyses.^a

Class	Subclass	Call Type	<i>n</i> =	Bout (<i>n</i>)	Peak (Hz)	Duration (s)	Band (Hz)	Start (Hz)
Low Frequency Harmonic	Trilled	Growl ^b	100	1	128	1	257	90
				<i>2</i>	<i>75</i>	<i>0.7</i>	<i>266</i>	<i>39</i>
	Complex	Whup ^b	33	1	132	0.7	249	112
				<i>1</i>	<i>81</i>	<i>0.2</i>	<i>82</i>	<i>158</i>
		Mod. Moan ^b	4	2	223	1.3	770	170
				<i>2</i>	<i>102</i>	<i>0.6</i>	<i>173</i>	<i>33</i>
		Desc. Moan	4	1	147	1.4	553	225
				<i>0</i>	<i>28</i>	<i>0.6</i>	<i>520</i>	<i>91</i>
	Simple	Groan	3	1	209	3.3	434	207
				<i>1</i>	<i>0</i>	<i>113.9</i>	<i>2</i>	<i>5</i>
	Var. Moan	3	1	180	2.5	477	341	
			<i>0</i>	<i>0</i>	<i>240.8</i>	<i>1</i>	<i>12</i>	
LFH Class Average			147	1.7	135	1.4	292	108.7
Pulsed	Complex	Swops	57	6	328	0.6	894	244
				<i>7</i>	<i>287</i>	<i>0.3</i>	<i>717</i>	<i>242</i>
				4	191	0.6	327	142
		Teepee	12	4	191	0.6	327	142
				<i>4</i>	<i>101</i>	<i>40.5</i>	<i>253</i>	<i>1</i>
				7	1732	2.1	3047	882
		Horse	4	7	1732	2.1	3047	882
				<i>5</i>	<i>3046</i>	<i>0.6</i>	<i>3337</i>	<i>1115</i>
				5	309	0.5	763	238
		Simple	Droplets	9	5	309	0.5	763
<i>3</i>					<i>140</i>	<i>0.1</i>	<i>795</i>	<i>146</i>
P Class Average			83	5.4	430	0.76	900	260
Noisy/Complex	Variable	Squeegie	8	5	766	2.2	1177	1006
				<i>10</i>	<i>698</i>	<i>1</i>	<i>1177</i>	<i>950</i>
				1	859	0.9	1126	724
				<i>0</i>	<i>491</i>	<i>0.4</i>	<i>604</i>	<i>200</i>
				1	380	1.1	480	269
	Harmonic	Asc. Shreik ^b	5	1	1701	1.6	6781	1459
				<i>0</i>	<i>1279</i>	<i>0.7</i>	<i>5204</i>	<i>974</i>
				1	1506	0.9	2740	1302
				<i>0</i>	<i>1452</i>	<i>0.2</i>	<i>2419</i>	<i>1197</i>
				4	1506	0.9	2740	1302
NC Class Average			27	2.1	986	1.4	3032	952
Tonal	Feeding Call ^b	43	1	460	16.6	101	459	
			<i>0</i>	<i>119</i>	<i>23.1</i>	<i>53</i>	<i>106</i>	

^aMean values are in bold and standard deviations below in italics. Variable descriptions can be found in Table I.

^bNaming precedents: “Growl” and “Whup” were set by Wild and Gabriele (2014); “Modulated Moan,” “Ascending Shreik,” and “Descending Shreik” by Dunlop *et al.* (2007); and “Feeding Call” by Cerchio and Dalheim (2001).

4. Noisy/complex calls

The noisy/complex (NC) vocal class was the least-represented vocal class ($n = 27$). There was 70% ($n = 19$) overlap between samples subjectively placed in this vocal class and samples quantitatively grouped into cluster 3. Within-class DFA correctly predicted the subclass for 93% of samples ($n = 25$), and correctly predicted call types for 100% of samples within the NC vocal class ($n = 27$). Samples in the NC vocal class were characterized by wide bandwidths, high peak frequencies, and high aggregate entropy (Table IV, Fig. 6). Results of a Wilcoxon Rank-Sum test indicate that the means of these three acoustic parameters—bandwidth, peak frequency, and aggregate entropy—varied significantly between vocal classes ($p < 0.0001$). *Post hoc* Steel-Dwass tests indicated the means bandwidth of NC calls is higher than calls in T and LFH vocal classes ($p < 0.001$), but not

significantly different from calls in the P vocal class ($p = 0.07$). The mean peak frequency of NC calls is significantly higher than calls in LFH and P vocal classes ($p < 0.0001$), but not significantly different from calls in the T vocal class ($p = 0.45$). Mean entropy of calls is significantly higher in the NC vocal class than in LFH or T vocal classes ($p < 0.0001$), but not significantly different than in the P vocal class ($p = 0.15$).

Samples in the NC vocal class fell into two subclasses: Harmonic and variable (Table IV, Fig. 6). Mean entropy levels for samples in this vocal subclass were significantly higher than in the variable subclass ($p = 0.008$), as were mean bandwidths ($p = 0.006$). Ascending shrieks* and descending shrieks* (Dunlop *et al.*, 2007) were broadband and harmonic in nature and were included in the harmonic subclass (Table IV, Fig. 6). Calls within the variable subclass were characterized by multiple inflections (slope reversal of

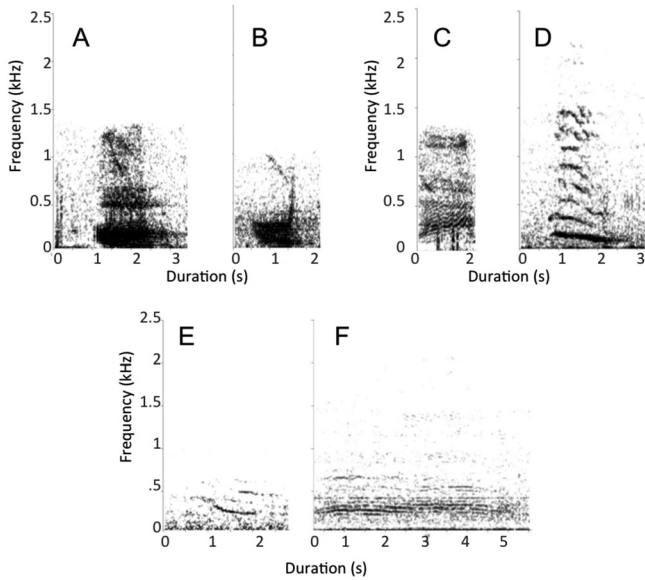


FIG. 3. Spectrograms of call types determined through aural-visual classification to belong to the low-frequency harmonic (LFH) vocal class. Subjectively determined call types are grouped by subclass: trilled subclass: [A] growl, [B] whup*; complex subclass: [C] modulated moan*, [D] descending moan; simple- [E] variable moan, [F] groan.

the fundamental frequency), and temporal patterns that varied widely from one call to the next (Table IV, Fig. 6). Squeezes, ahoogas, and aerial trumpets were considerably less “musical” than other call types in the NC vocal class, contained inconsistent temporal structure, and were included in the variable subclass (Table IV, Fig. 6).

IV. DISCUSSION

Humpback whales are well known for the complexity of their vocal behavior on the breeding grounds. This study

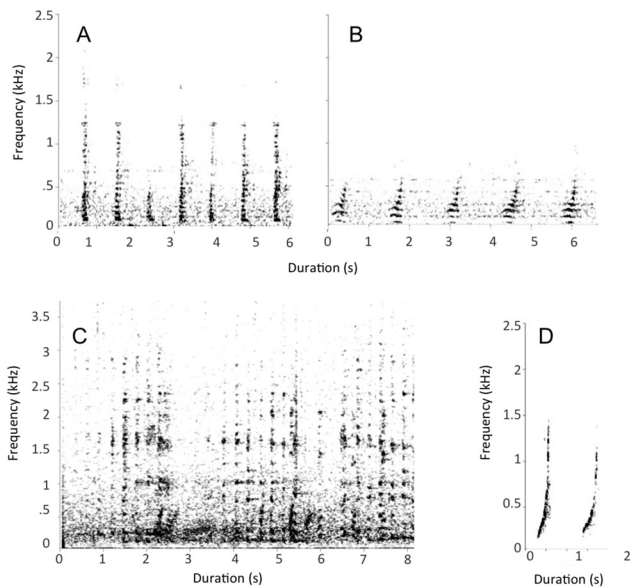


FIG. 4. Spectrograms of call types determined through aural-visual classification to belong to the pulsed (P) vocal class. Subjectively determined call types are grouped by subclass. Complex subclass: [A] swops, [B] teepees, [C] horses. Simple subclass: [D] droplets. Note difference in frequency scale for spectrogram of Horse call (max frequency 4 kHz) versus other spectrograms (max frequency 2.5 kHz).

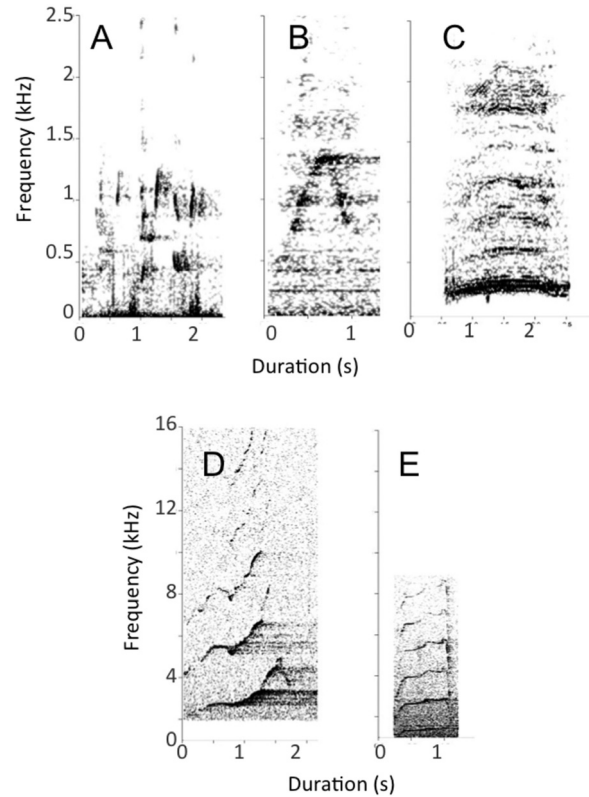


FIG. 5. Spectrograms of call types determined through aural-visual classification to belong to the noisy/complex (NC) vocal class. Subjectively determined call types are grouped by subclass. Frequency modulated subclass: [A] squeegie, [B] trumpet, [C] ahooga. Harmonic subclass: [D] ascending shriek*, [E] descending shriek. Note difference in frequency scale for spectrograms in frequency modulated subclass (max frequency 2.5 kHz) versus the harmonic subclass (max frequency 16 kHz).

demonstrates humpback whales also produce a diverse array of vocalizations on an Alaskan foraging ground and is the first to quantitatively classify non-song call types on a foraging ground. The combined results of AV classification and hierarchical agglomerative cluster analysis suggest that, based on acoustic parameters, non-song vocalizations documented in this study fall into 16 call types nested in four vocal classes. The 16 call types identified by this study add a greater degree of specificity to the broad call descriptions proposed for Southeast Alaska by [Thompson *et al.* \(1986\)](#)

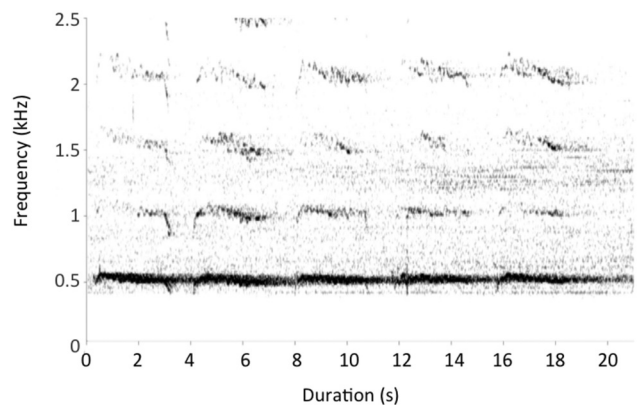


FIG. 6. Spectrogram of the sole call type determined through aural-visual classification to belong to the tonal (T) vocal class: feeding call.

and form the foundation for a comprehensive catalog of non-song calls from the region. Further, this study identifies an inherent acoustic structure in humpback whale calling from this region that has not been previously identified, and may exist elsewhere.

On the basis of visual analysis and comparison of call parameters reported in the literature, it appears that in general, humpback calls recorded in Southeast Alaska are slightly higher in frequency than social calls described for eastern Australia (Dunlop *et al.*, 2007), but they appear to be similar in frequency to calls described for the North Atlantic foraging grounds (Stimpert *et al.*, 2011). Fewer unique call types are identified in this catalog than have been identified for the east Australian migratory region (Rekdahl *et al.*, 2013). Differences in methodology preclude direct comparison between the number of discrete calls present in the North Atlantic versus Southeast Alaska; however, more call types are quantitatively described here than have been described for the North Atlantic population (Stimpert *et al.*, 2011).

Some similarities in call types from the three regions are evident. The whup call appears to have a cosmopolitan distribution; it was visually and aurally similar to vocalizations recorded in both east Australia (“wop”; Dunlop *et al.*, 2007) and the North Atlantic (“wop”; Stimpert *et al.*, 2011), and the call was occurred frequently in both studies. Further, Stimpert *et al.* (2011) cite unpublished data confirming the presence of this call type on the Hawaiian breeding grounds, and aural examination of unpublished data confirms the presence of the call type in Cormorant Channel in British Columbia, Canada as well. This call type was present and common throughout a four-year study in east Australia (Rekdahl *et al.*, 2013) and appears to correspond to the moans reported in the report of Thompson *et al.* (1986) from Southeast Alaska; furthermore, this call was documented repeatedly in Glacier Bay National Park between 2007 and 2010 (Wild and Gabriele, 2014). The occurrence of this call type in independent populations suggests that its use is not culturally dependent. Investigation into the longevity and stability of this call over greater time scales and between populations would provide valuable insight into its function.

Similarly, three call types—ascending shrieks, descending shrieks, and modulated moans—were visually similar to spectrograms reported by Dunlop *et al.* (2007) to be song units. In this study, the three call types were poorly represented, making up only a small portion of the data set, but they did appear to be stereotyped (corroborated by high levels of classification agreement) and occurred in short calling bouts similar in structure to song. Song was not recorded in this study; however, comparisons to song recorded in November 2012 in Glacier Bay National park (C. Gabriele, personal communication) confirmed that the same three call types were used as song units in Southeast Alaska in the same year. Samples from other regions were not subjected to the aforementioned classification system, so it is not possible to extend inference directly; however, it is possible that continued recording in Frederick Sound into the fall may have resulted in the detection of singing humpback whales.

Given the wide variety of sounds that humpback whales produce, overlap in the nomenclature between the populations has become a concern. To avoid replicating names while simultaneously maintaining naming precedents from the region, the authors suggest prefacing names with an abbreviation of the region where the call was produced (i.e., SEAK-Whup) until such time as a quantitative analysis can be conducted comparing vocalizations between populations.

A. Classification methods

There are inherent problems with each of the three classification methods employed in this study when used independently. Although there is a high degree of subtlety that may be assessed by a human observer using AV classification, when used in isolation AV classification is highly subjective, particularly if there is individual or inter-group variation. Observers may not examine vocalizations with the same degree of scrutiny, leading some observers to broadly classify similar vocalizations as one call type, while other observers may delineate call uniqueness at a level explained by individual variation. Statistical methods, such as hierarchical cluster analyses, can allow for more objective assessments of group membership. Cluster analyses reduce the likelihood of observer bias by quantitatively identifying groupings in the data set that may be overlooked; however, cluster analyses are not entirely objective as the investigator chooses both acoustic parameters and the level at which to limit grouping inferences. Alternatively, DFA is a good tool for quantitatively validating predetermined group membership, yet cannot identify structure inherent in the data set and is contingent on predefined groupings and observer-defined parameters.

The problems inherent to the three classification methods can be minimized when the methods are employed concomitantly. In this study, the cluster analysis grouped calls into vocal classes and the DFA corroborated their membership; however, by incorporating a human observer, salient differences in acoustic parameters between vocal classes were detected that would have been otherwise overlooked. For example, acoustic parameters identified through AV analysis to be good indicators of call types within vocal classes were found to vary significantly between vocal classes and vocal subclasses. These acoustic parameters could not be uniquely identified as discriminating features by either the cluster analyses or DFA. More generally, the hierarchical structure identified by AV classification and hierarchical cluster analyses was strengthened by high agreement with DFA. The corroborating results based on multiple classification methodologies allowed for vocalizations to be identified to the lowest possible level of specificity with a high degree of confidence and repeatability.

While applied here to humpback whale non-song vocalizations, the high level of corroboration suggests that this methodology may be appropriate for classifying calls in other species that contain broad and diverse acoustic repertoires. AV analyses and cluster analyses were used to classify beluga vocalizations in Canada’s Churchill River (Chmelnitsky and Ferguson, 2012), and arguably the study

would have benefited from the validating effect of DFA. Similarly, foundational studies of bowhead whale vocalizations rely almost exclusively on aural-visual classification despite a growing number of unique sound types (Clark, 1982; Clark and Johnson, 1984; Würsig *et al.*, 1993; Stafford *et al.*, 2008; Delarue *et al.*, 2009), many of which are similar to humpback whale vocalizations. Automated detection of vocalizations is appealing, particularly with large data sets; however, even robust detectors are dependent on training sets (Binder and Hines, 2014). The three-part method described here may be an effective tool for developing representative training sets that can be applied to larger databases. Further, humpback whale vocalizations can be difficult to discern from other baleen whale species that are often detected using PAM across large temporal scales—notably right whales and bowhead whales—and thus a known catalog of humpback whale vocalizations is useful for studies where humpback whales may act as a confounding factor.

B. Vocal continua

Despite the general efficacy of the three-part classification method, not all call types were classified with the same degree of confidence. For example, calls in the T and NC vocal classes and P simple subclass are comparatively discrete and were classified with a high degree of agreement between the three methods. In contrast, whups and growls were acoustically similar resulting in lower overall classification agreement at the call type level. A similar phenomenon was observed for calls in the P complex subclass. Although samples were grouped in the same vocal class with a high degree of agreement across classification methods, at finer scales distinguishing differences between samples met with moderate, though reduced, success. The swop call was visually and aurally different from other call types; however, it was structurally more variable than other call types. AV examination revealed that this call appeared to be intermediate between other call types, namely, the teepee call and the horse call. Anecdotally, in one 30-s recording, a single animal was recorded transitioning from a vocalization that was clearly a whup call into a series of clearly delineated swop calls and further into a series of teepee calls, indicating that some call types may have fluid boundaries that can be identified through the combined classification methods.

Vocal continua pertaining to humpback whale non-song vocalizations were suggested in the North Pacific population (Silber, 1986) and in the North Atlantic and eastern Australian populations (Dunlop *et al.*, 2008; Stimpert *et al.*, 2011). Similarly, Clark (1982) reported both continuous and discrete calls in southern right whales, and found that some call types in the continuum were more common than others. It is possible that during some activities (e.g., courtship displays, cooperative foraging) discrete calls may be favored, while when less discrete social interactions occur (e.g., contact calling), calls from the call continuum may be favored (Bradbury and Verehncamp, 2011). This has been observed in northern right whales, where males produce a highly stereotyped “gunshot” call in association with mate attraction, while females favor a diverse repertoire of calls when interacting in surface active groups (Parks and Tyack, 2005; Parks *et al.*, 2011). On

breeding grounds, humpback whale song is highly stereotyped and has been associated with a specific behavioral context (Tyack, 1981; Winn *et al.*, 1981). Similarly the feeding call, which was the most stereotyped call in this study based on AV analysis and classification agreement, has been associated with coordinated foraging events in Southeast Alaska (D’Vincent *et al.*, 1985; Cerchio and Dalheim, 2001; Sharpe, 2001). Conversely, in migrating humpbacks the wop call, which is visually and acoustically similar to the whup call described in this study, has been proposed to serve multiple functions, including acting as a contact call, an inter- or intra-group social call, and a mother-calf affiliation call (Dunlop *et al.*, 2008).

One of the strengths of the three-part method lies in the ability to identify differences in call types regarding their discreteness. High levels of corroboration indicate stereotyped calls, while low levels of agreement between the three methods indicate highly variable calls. In the absence of this sort of validation variability is either assessed qualitatively based on AV analyses, as in the report by Dunlop *et al.* (2007), or results are broadly reported and lack detailed inference, as in the report by Stimpert *et al.* (2011). On the basis of the breadth of their non-song repertoire and the ability of the combined methodology to identify varying degrees of call discreteness humpback whales are an ideal specimen for investigating the relationship between call stereotypy and call function in marine communication.

V. CONCLUSIONS

This study uses a combined three-part classification method to present the first quantitatively described catalog of non-song calls for Southeast Alaskan humpback whales and expands the known vocal repertoire for humpback whales in the population. The hierarchical classification of sounds into classes, sub-classes, and call types was based on the acoustic properties of each sound independent of behavioral or environmental context. Catalogs generated in this way are critical for testing for usage differences between sounds and investigating their biological relevance. Similar to vocalizations reported for humpbacks from other regions and for other species, humpback whale vocalizations in Southeast Alaska appear to consist of a combination of discrete and continuous calls, warranting future investigation into call stereotypy as a function of behavioral contexts. Additional research is needed on call stability, calling behavior as a function of age, gender, and reproductive status, from other populations, and throughout their migratory range. It has been suggested that publications that are digitally available be accompanied by spectrograms, sound files, and associated recording information. This would greatly enhance the ability to compare call types between contexts, regions, and species. Copies of sample call types referenced in this paper are available by request or can be found online at <http://mfournet.wordpress.com/sounds>.

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