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North Atlantic right whale (*Eubalaena glacialis*) acoustic behavior on the calving grounds

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Abstract: Passive acoustic monitoring is a common method for detection of endangered North Atlantic right whales. This study reports on the acoustic behavior of right whales on the winter calving grounds to assess their acoustic detectability in this habitat. In addition to known call types, previously undescribed low amplitude short broadband signals were detected from lactating females with calves. The production of higher amplitude tonal calls occurred at lower rates for lactating females than from other age/sex classes suggesting that passive acoustic monitoring may be less effective in detecting mother-calf pairs in this critical habitat area.

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1. Introduction

North Atlantic right whales (*Eubalaena glacialis*) are an endangered baleen whale species found off the eastern coast of North America. Passive acoustic monitoring is used to aid in detecting right whale presence in particular habitat areas to aid in conservation (Van Parijs *et al.*, 2009). The North Atlantic right whale acoustic repertoire has been studied extensively on the spring and summer feeding grounds (Matthews *et al.*, 2001; Parks and Tyack, 2005; Parks *et al.*, 2011) indicating seasonal variation in signal production (Bort *et al.*, 2015; Mellinger *et al.*, 2007; Van Parijs *et al.*, 2009) and variation in call types and rates in different age and sex classes (Parks *et al.*, 2011). These studies indicate that all age classes and sexes on the feeding grounds produce a tonal stereotyped upsweep signal, referred to as the "upcall" (Parks *et al.*, 2011), which is most commonly used in North Atlantic right whale passive acoustic monitoring applications (Van Parijs *et al.*, 2009).

Less is known about the acoustic communication behavior of individual North Atlantic right whales outside of the feeding grounds. Passive acoustic monitoring studies have reported detections of upcalls along the migratory corridor on the U.S. mid-Atlantic coastline (Hodge *et al.*, 2015; Salisbury *et al.*, 2015). One study describing the signal production of juvenile and adult right whales in surface active groups on the winter calving grounds has been published (Trygonis *et al.*, 2013) showing similarities to signal types described on the feeding grounds (Parks and Tyack, 2005). A long-term passive acoustic monitoring study in the Southeastern U.S. documented upcall sound production (Soldevilla *et al.*, 2014), however a recent study from towed array recordings during focal-follows of mother-calf pairs indicated relatively low rates of upcall production by mothers with young calves during the day on the calving grounds (Cusano *et al.*, 2018).

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This study was undertaken to describe the acoustic repertoire and call rates of individual North Atlantic right whales on the winter calving grounds. Acoustic recording tags were attached with suction cups to detect all signals, even those of low amplitude, to describe the call types and call rates for individual right whales on the calving grounds off the coasts of Florida and Georgia during the winter months. These data can help inform passive acoustic monitoring efforts in this critical habitat area for this endangered species.

2. Materials and methods

2.1 Data collection

Data were collected in 2006 and 2014–2016 in the Southeastern United States off the coasts of Georgia and Florida during the period of peak presence of right whales between January and February. Suction-cup attached archival acoustic recording tags (DTAG) (Johnson and Tyack, 2003) were used to collect acoustic data from individual right whales following methods described in Nowacek *et al.* (2001). These tags were equipped with a hydrophone for acoustic data sampling as well as a three-axis accelerometer, magnetometer, and pressure sensor. Acoustic data were sampled at either 64 or 96 kHz depending on the year of deployment. Acoustic system sensitivity of the tags was -171 dB re 1V/μPa with a high pass Butterworth filter at 400 Hz to minimize flow noise on the tag. Orientation sensors were sampled at 50 Hz. Whales were followed within 200 m for a period of up to 1 h after tag attachment to confirm orientation of the suction cup tag placement and to collect data including the presence of dolphins, nearby vessels, or other whales within 1 km of the tagged whale. After 1 h, the tagging vessel stopped following the whales. Tags were relocated after they detached from the whale using a VHF transmitter in the tag.

Identification photographs were taken of the whales to use individually distinct markings and callosity patterns to confirm identity (Kraus *et al.*, 1986). These identifications, including the age and sex of each tagged whale, were confirmed by the New England Aquarium, which manages the North Atlantic right whale consortium identification database [North Atlantic Right Whale Consortium (2016)]. Whales were classified by age as juvenile ($\leq$9 years of age) or adult (9 years or greater) and identified as male or female based on the consortium database. Adult females were further categorized as pregnant if subsequently seen within the same season accompanied by a calf or lactating if accompanied by a young calf.

2.2 Acoustic analyses

Tag records greater than 20 min in duration were retained for analysis. Acoustic recordings were reviewed for the presence of right whale sounds using Raven Pro 1.5 (Bioacoustics Research Program, 2014). Spectrograms were generated with a 4096-point fast Fourier transform (FFT), Hann window, 90% overlap with a frequency resolution of 15.6–23.4 Hz (64–96 kHz sampling).

Call types. Determining whether the focal (tagged) whale produced calls recorded on an acoustic recording tag can be challenging for baleen whales (Goldbogen *et al.*, 2014). All calls recorded on the tags were identified and calls were assigned as likely produced by the focal whale based on the following three criteria: (1) signal-to-noise ratio (SNR) $\geq$5 dB; (2) presence of high frequency components and harmonics of the signal (>2 kHz), and (3) absence of audible exhalation or blow sounds on the audio record when the whale with the tag was submerged >3 m from the surface. The water depth in the habitat is <50 m with mother-calf pairs predominately sighted in water depths of 10–20 m (Garrison, 2007) limiting the potential propagation range of low frequency acoustic signals. Other whales close enough to produce high SNR signals would also likely be detected through the presence of exhalation sounds.

In 2/3 of the juvenile whale tag records (#3442 and #3430) high SNR calls were recorded on the tags when the whales were in close proximity to other right whales as confirmed by the presence of multiple whale exhalations on the audio record when the tagged whale was at depth. As the objective of this study was to document call types and call rates of right whales on the calving grounds to inform passive acoustic monitoring, these sounds would still be indicative of the tagged whale's presence and behavioral context, even if they were not produced by the tagged whale. For all other records (all pregnant females and lactating females), there was no acoustic evidence in the tag record of any other associated whales during tag attachment and no evidence during the visual focal follows of any other whales within visual range from the vessel platform ($\sim$6 km based on an eye height above sea level of approximately 2.5 m). Mother-calf pairs are rarely sighted in close proximity to other whales on the calving grounds with only 17/1361 sightings over a period of 10 years of surveys (Gowan and Ortega-Ortiz, 2014).

Call parameters. All acoustic records were low-pass filtered and re-sampled at 16 kHz for SNR analysis from 20 Hz–8 kHz. A single-pole low-frequency emphasis filter was used to compensate for the high pass filter in the tag recordings (as in Stimpert *et al.*, 2011). Flow noise from rapid movements can dominate the low frequency noise from tag records (Goldbogen, 2006). Sound clips that included splashing sounds, detectable flow noise from whale movement, or other non-acoustic sources of recording noise were removed from further analysis. SNR was calculated by measuring the root-mean-square (RMS) sound level of a window containing 90% of the energy of the signal of interest and subtracting the RMS ambient noise level in a 500 ms period in the recording immediately before the signal using custom scripts in MATLAB R2013a (Mathworks, Inc., Natick, MA). Only signals with a SNR $\geq$5 dB were retained for subsequent acoustic measurements.

The 16 kHz sound files were used for the acoustic measurements. Measurements included duration (s), peak frequency [frequency at the time of maximum signal power (Hz)], center frequency [frequency that divides the call into two frequency intervals of equal energy (Hz)], and 90% bandwidth [the difference between the frequencies that divide the call into two frequency intervals containing 95% and 5% of the energy in the selection (Hz)]in Raven Pro 1.5. For tonal calls, including *Upcalls*, *Low calls*, and *High calls*, the start and end frequencies of the fundamental were also measured from the spectrogram in Raven Pro 1.5 with a 4096 FFT, Hann window, with 90% overlap for a frequency resolution of 3.9 Hz.

Upcall depth and call rate. The depth of the tagged whale at the time of *Upcall* production was determined from the pressure record from the DTAG with a resolution of 0.5 m H_2O (Johnson and Tyack, 2003).

The call rate was calculated as the total number of *Upcalls* detected divided by the total duration of the tag recording. The average *Upcall* rates were calculated for all tags and separately for each reproductive class of whale (juvenile, pregnant, and lactating) to assess differences related to reproductive state.

3. Results

3.1 Data collection

A total of 16 DTAGs with attachment durations >20 min were attached to right whales on the Southeastern U.S. calving grounds in 2006 (N = 4), 2014 (N = 4), 2015 (N = 1), and 2016 (N = 7) for a total of 107.9 h of acoustic data (Table 1). These included 2 juvenile males, 1 juvenile female, 2 pregnant females, and 11 lactating females. One individual (ID #3101) was tagged during late pregnancy, and then tagged 3 weeks later when accompanied by a young calf in 2016.

3.2 Acoustic analyses

Call types. Acoustic review of the tag acoustic records revealed a range of previously described right whale call types (Parks and Tyack, 2005), including the stereotyped *Upcall*, *Low*, *High* tonal calls, *Hybrid* calls, and broadband signals including *Gunshot* and *Pulsive* signals (Fig. 1). During review of the calls produced by EGNO #3101 when pregnant, a low amplitude broadband sound, termed here as a "*Paired grunt*," was distinctly produced paired with a series of *Upcalls* [Fig. 2(a), Mm. 1]. The signal was produced prior to the production of the *Upcall* [mean ± standard deviation (SD) (min–max) time between signals; 1.2 ± 0.36 s (0.28–2.5 s), n = 19 paired calls] providing high confidence that this sound was produced by the tagged whale. After discovery of this novel signal type, all other tags were screened for this sound. During this screening the *Paired Grunt* was identified on five tags (Table 1), but similar sound types consisting of either 1 (*Single pulse*) (Mm. 2) or 2 (*Double pulse*) (Mm. 3) signals without an associated tonal call were detected in 10 tags (Fig. 2). Additionally, calls associated with calves from a previous study (Root-Gutteridge *et al.*, 2018) were detected on 5 out of 11 lactating female tags (Fig. 2).

Mm. 1. Audio file of *Paired grunt* with an *Upcall*. This is a file of type ".wav" (314 KB).

Mm. 2. Audio file of "*Single pulse*." This is a file of type ".wav" (111 KB).

Mm. 3. Audio file of "*Double pulse*." This is a file of type ".wav" (120 KB).

Call parameters. Call parameters for all call types with a SNR $\geq$ 5 dB are summarized in Table 2.

Table 1. Summary of tag attachment data including date of tag attachment, right whale ID provided by the North Atlantic Right Whale Consortium, Age/Sex/Status (J = Juvenile; P = Pregnant; L = Lactating), Duration (Dur.) of tag audio recording, number of detected focal calls by call type category. Up = *Upcall*; Low = *Low Calls*; Hi = *High Calls*; Hyb = *Hybrid calls*; PG = *Paired Grunt*; SP = *Single pulse*; DP = *Double pulse*; Gun = *Gunshot*; Pul = *Pulsive*; C = *Calf.*

Date	ID	Age/ Sex/ Status	Dur. (h)	Up	Low	Hi	Hyb	PG	SP	DP	Gun	Pul	C
1/21/06	#3442	2/M/J	1.35	10	18	0	3	12	0	0	0	4	n/a
1/24/06	#3323	3/M/J	1.68	0	0	0	0	0	0	0	0	0	n/a
1/24/06	#3430	2/F/J	0.90	2	0	6	9	5	0	0	0	14	n/a
1/28/06	#1151	>26/F/P	18.50	0	1	0	0	0	0	0	0	0	n/a
2/9/14	#2123	23/F/L	1.55	6	3	0	0	0	1	0	0	4	0
2/10/14	#2040	24/F/L	5.82	6	0	0	0	0	17	2	0	4	45
2/18/14	#3157	13/F/L	11.60	0	0	0	0	0	41	7	0	2	2
2/25/14	#2645	18/F/L	5.57	0	0	0	0	0	9	2	0	7	0
2/21/15	#3292	13/F/L	23.08	0	0	0	0	0	79	25	0	12	0
1/25/16	#3101	15/F/P	5.00	38	0	1	4	26	0	0	1	2	n/a
1/30/16	#3405	12/F/L	4.75	0	0	0	0	0	30	24	0	7	0
1/31/16	#1281	>35/F/L	6.73	0	0	0	0	0	45	11	0	7	0
2/1/16	#1810	>28/F/L	1.75	0	0	0	0	0	0	0	0	0	0
2/17/16	#3101	15/F/L	4.93	0	2	0	0	1	38	5	0	75	6
2/17/16	#1281	>35/F/L	2.83	2	2	0	0	2	34	14	0	1	1
2/22/16	#3317	13/F/L	11.80	0	0	0	0	0	42	10	2	12	7
Totals			**107:51**	**64**	**38**	**7**	**16**	**46**	**336**	**100**	**3**	**151**	**61**

Upcall depth and call rate. The average depth of *Upcall* production was 8.3 ± 4.4 m (range of 0.4–15.4 m). The average upcall rates were calculated for the overall tag recording data and separately for each age class of whale (juvenile, pregnant, and lactating). Overall call rates ranged from 0 to 7.4 *Upcalls*/h. *Upcall* rates were much higher for juvenile (3.2 ± 3.8 *Upcalls*/h) and pregnant females (3.8 ± 5.4 *Upcalls*/h) than for lactating females (0.51 ± 2.4 *Upcalls*/h).

4. Discussion

These data provide details on the calling behavior of North Atlantic right whales on the calving ground off the southeastern U.S. In addition to a variety of previously described call types for right whales, a new low-amplitude, short duration signal was detected from acoustic recording tags attached to whales in this habitat. The discovery

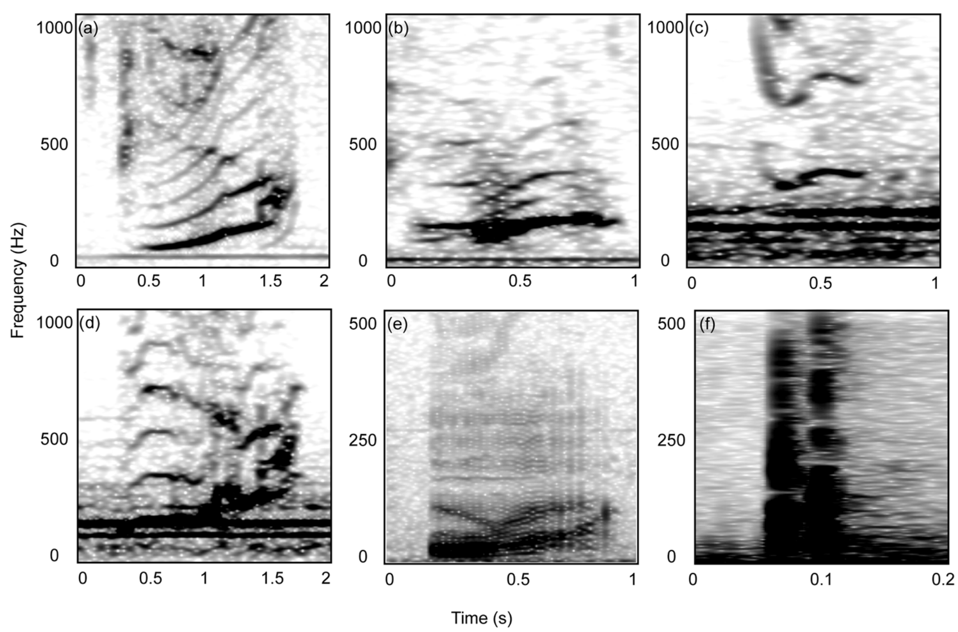

Fig. 1. Example spectrograms for previously described call types: (a) upcall, (b) low tonal, (c) high tonal, and (d) hybrid, (e) pulsive, and (f) gunshot. Spectrogram settings with 16 kHz sampling, 2048 FFT, Hann window, 90% overlap for (a)–(d), 1024 FFT for (e) and (f).

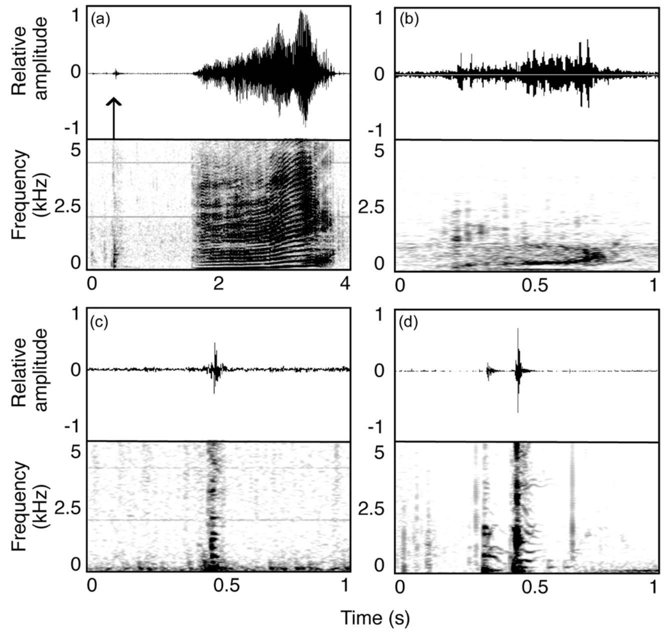

Fig. 2. Waveform and spectrograms of new call types including (a) paired grunt with an upcall (paired grunt marked by arrow in waveform to highlight relative amplitude), (b) calf calls, (c) single pulse, and (d) double pulse sounds. Spectrogram settings with 16 kHz sampling, 1024 FFT, Hann window, 90% overlap.

of these sound types was possible through the advantages of acoustic recording tags attached directly to the study animal, allowing for passive recording at close range to detect these low amplitude signals. Previous studies using single stationary hydrophones or towed hydrophone arrays in close proximity (<200 m) to individual whale did not detect these signals (Trygonis *et al.*, 2013; Cusano *et al.*, 2018). These signals, therefore, while potentially important for communication over short ranges, are of limited value for passive acoustic remote sensing of this species.

The *Paired grunts* were the first of these low-amplitude signals to be detected during analysis. These signals were produced immediately before higher amplitude tonal signals by multiple whales, including juveniles, pregnant females, and lactating

Table 2. Summary of call parameters for all call types with an SNR ≥ 5 dB. Reporting mean ± SD (min–max) for each measurement. The start and end frequency of the fundamental frequency are reported for tonal calls (*Upcall*, *Low*, *High*, *and Hybrid*).

Call type	*N*	Duration (s)	Center frequency (Hz)	Peak frequency (Hz)	90% Bandwidth (Hz)	Start Frequency (Hz)	End Frequency (Hz)
Upcall	34	1.12 ± 0.27 (0.48–1.52)	350 ± 366 (106–1301)	132 ± 26 (78–203)	1741 ± 703 (23–3285)	93 ± 22 (62–138)	193 ± 52 (123–338)
Low	20	0.91 ± 0.24 (0.41–1.51)	581 ± 508 (106–1543)	187 ± 277 (86–1363)	1890 ± 741 (150–3148)	97 ± 24 (58–144)	133 ± 22 (93–174)
High	3	0.83 ± 0.07 (0.74–0.88)	721 ± 309 (371–953)	818 ± 591 (211–1390)	1162 ± 570 (734–1809)	463 ± 38 (421–495)	367 ± 209 (186–595)
Hybrid	10	0.98 ± 0.30 (0.47–1.40)	703 ± 422 (121–1398)	375 ± 259 (106–891)	1894 ± 610 (761–2781)	316 ± 227 (115–640)	297 ± 178 (115–640)
Paired grunt	10	0.15 ± 0.07 (0.03–0.25)	551 ± 432 (63–1481)	402 ± 531 (47–1758)	2139 ± 606 (1281–3004)		
Single pulse	27	0.10 ± 0.05 (0.04–0.27)	429 ± 305 (164–1754)	290 ± 154 (35–750)	1170 ± 863 (215–3684)		
Double pulse	10	0.13 ± 0.08 (0.07–0.34)	353 ± 134 (160–563)	294 ± 85 (168–404)	1339 ± 772 (344–2791)		
Gunshot	2	0.13 ± 0.06 (0.09–0.17)	957 ± 552 (566–1348)	973 ± 536 (594–1352)	1518 ± 174 (1395–1641)		
Pulsive	33	0.65 ± 0.49 (0.11–2.36)	524 ± 342 (117–1425)	406 ± 311 (53–1441)	1468 ± 1219 (238–5486)		
Calf	3	0.34 ± 0.39 (0.09–0.79)	294 ± 156 (121–421)	215 ± 223 (51–469)	691 ± 281 (516–1016)		

females. The production of this signal was tightly linked temporally to the higher amplitude signals, with consistent timing between the *Paired grunt* signal production before a tonal call type was produced. It appears that this signal may be an unintentional by-product of higher amplitude signal production, as not all individuals generated this sound type prior to their tonal calls. Individuals who did make *Paired grunt* signals did so before most of their higher amplitude calls, suggesting individual variation in sound production. These *Paired grunt* signals may provide information that can improve our understanding of the sound production mechanisms or development of sound production by baleen whales, which remain poorly understood (Reidenberg and Laitman, 2007). The *Single Pulse* and *Double Pulse* signals were detected exclusively from tags attached to lactating females with dependent calves under 3 months of age. These signals have also not been previously described from any right whale species. These signals are similar in amplitude to the *Paired grunts*, but were shorter in duration and lower in frequency. Given their low amplitude, these signals would only be detectable over short ranges. It is unclear whether these signals are intentionally produced for communication or a by-product of some other behavior specific to lactating females, such as nursing. A previous study of vocal behavior of mother-calf pairs in humpback whales (*Megaptera novaeangliae*) described similar low amplitude pulsed signals (Zoidis *et al.*, 2008), suggesting that these signals may be produced by mother-calf pairs from multiple baleen whale species.

Call production depths of *Upcalls* were on average deeper (8 m) in this habitat than previously reported for North Atlantic right whales in the Bay of Fundy, Canada ($<$5 m) (Parks *et al.*, 2011). One potential explanation for this observation is that given the well mixed water temperature profile and shallow water column depth in this habitat, the depth of lowest transmission loss may be deeper than in other habitats. Further analyses of propagation characteristics of right whale signals in this habitat are necessary to test this hypothesis, which would also facilitate comparisons of detection ranges for right whale signals across their migratory range.

Call rates of the most commonly detected call type for passive acoustic monitoring of this species, *Upcalls*, were relatively high for both juvenile and pregnant females in this habitat. Previous studies have reported grouped tonal call rates of between 0 and 720 calls/h on the foraging grounds of the North Atlantic right whales in New England and Canadian waters (Matthews *et al.*, 2001; Parks *et al.*, 2011). In our study, average *Upcall* rates were 3.21–7.6 calls/h for individual juveniles and pregnant females. Mother-calf pairs, in contrast, had extremely low rates of *Upcall* production in our study. *Upcall* rates were only 0.51 calls/h for mother-calf pairs, with only 3 of 11 lactating females producing any *Upcalls* during the period of tag attachment, which lasted up to 23 h. Therefore, passive acoustic monitoring in the Southeast U.S. calving grounds may be biased toward detections of juvenile and pregnant whales, while potentially missing detections of right whales when only mother-calf pairs are present near an acoustic receiver. This is a major conservation concern and justifies the need for continued visual monitoring during the calving season in this habitat, as, importantly, passive acoustics alone is unlikely to detect calls when only mother-calf pairs are in a habitat area.

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