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Principal component analysis of song units produced by humpback whales (*Megaptera novaeangliae*) in the Ryukyu region of Japan

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Abstract

A total of 4681 units from humpback whale, *Megaptera novaeangliae*, songs were obtained around Ryukyu Islands, Japan, from 1991 to 1997. Based on aural and spectrographic analysis, we recognized 32 unit types and divided into four categories; harmonic, amplitude modulated, impulsive and complex sounds. Peak frequency of the majority of units were higher than the range of peak frequency of ambient noise in Ryukyu region, suggesting that humpback whale songs have been under selective force from environmental noise conditions. We classified all unit types into nine groups based on patterns from principal component analysis (PCA). Within a unit group, no clear boundary among unit types was found. Some unit groups occurred more often than others; H_1, H_4 and A_2 occurred every year, while sound types C_1 occurred during only 1992. Possible biological significance about sounds produced by humpback whales was discuss based on the occurrence of each unit group in different theme types.

Key words: humpback whale, song, sounds, principal component, Japan.

Introduction

Humpback whales, *Megaptera novaeangliae*, are widely distributed in all oceans of the world. Their life cycles are clearly divided into two parts. In spring, summer and autumn they feed in high latitude waters and in late autumn they migrate to low latitude waters, where mating and calving take place (Gaskin, 1982; Baker & Herman, 1984). In the North Pacific, the Okhotsk, around the Aleutian chain, the Bearing Sea, the Gulf of Alaska, off southeast Alaska, and off central California are known as feeding regions (e.g., Nishiwaki, 1966; Nemoto, 1978; Darling & Jurasz, 1983; Baker *et al*., 1986), and wintering has been observed in three regions, around the Hawaii Islands, off coastal Mexico and in south Japanese waters around the Ryukyu and Bonin Islands (e.g., Nishiwaki, 1966; Herman & Antinoja, 1977; Baker & Herman, 1981; Darling & Jurasz, 1983; Darling & Mori, 1993).

Humpback whales produce long, complicated sounds under water during the breeding season (Payne & McVay, 1971). Payne & McVay (1971) found these sounds repeated in a pattern referred to as ‘song’. Song has a hierarchical structure, i.e., individual sounds termed ‘units’ are grouped into ‘phrases’, phrases are grouped into ‘themes’, and themes are grouped into songs (Payne & McVay, 1971).

Humpback whales in a given geographical region change their songs during the breeding season, but whales within a region sing almost the same version of song, at any given time (Winn & Winn, 1978; Winn *et al*., 1981; Guinee *et al*., 1983; Payne *et al*., 1983; Payne & Payne, 1985). There are significant differences in songs produced from whales among geographically isolated oceans, but there are some similarities in songs among different breeding regions within the same ocean (e.g., Winn & Winn, 1978; Winn *et al*., 1981; Payne & Guinee, 1983; Helweg *et al*., 1990; Helweg *et al*., 1992; Cerchio, 1993; Helweg *et al*., 1998; Guan *et al*., 1999; Maeda *et al*., 2000).

Many studies on humpback whale songs have focused on the similarity or dissimilarity of song structure among regions, or the change of song structure within or between years. Detailed study on acoustic characteristics of individual song units was rare (e.g. Mednis, 1991). In most studies, classification of units in songs relied on qualitative analysis, such as aural impression or visual inspection of sound spectrograms (e.g., Winn & Winn, 1978; Winn *et al*., 1981; Cato, 1984; Cato, 1991; Mednis, 1991). Because song units clearly are patterned, qualitative methods for classification are applicable. However, these methods do not quantitatively explore the relationship among different units.

Although the function of songs remains unknown, observations from previous studies suggested a communicative function (Winn & Winn, 1978; Tyack, 1981; Helweg *et al*., 1992). Knowledge of the acoustic characteristics of song units and of the relationship among different unit types contributes to functional or structural understanding of songs.

Principle component analysis (PCA), a multivariate statistical method is a helpful method in classification or grouping, which reduces a large number of variables to a small number of factors that explain the relative importance of variables in classification (Sparling & Williams, 1978). This method has been applied to the studies of animal vocalizations (Sparling & Williams, 1978; Martindale, 1980*a*, 1980*b*; Clark, 1982).

In this study, different unit types were identified based on aural and spectrographic analysis from humpback whale songs recorded around the Ryukyu Islands, Japan. We presented acoustic characteristics of each unit types. To explore the relationship among unit types and to group unit types that have similar acoustic characteristics, we conducted on principal component analysis (PCA). Possible biological significance about sounds produced by humpback whales was discuss based on the occurrence of each unit group in different theme types.

Materials and Methods

We recorded humpback whale songs around the island of Zamami, Ryukyu Islands, Japan from 1991 to 1997. Recordings were conducted from a drifting boat with the engine off. We recorded songs using an Oki ST-1020 hydrophone with 30 m cable, an Oki SW-1020 preamplifier, and a Sony TCD D-3 digital/audio tape deck. We usually filtered out signals <10 Hz to eliminate ambient noise. This recording system was flat $\pm$ 3 dB from 20 Hz to 22 kHz in frequency response. Initial inspection of units on sound spectrogram (a Kay CSL model 4300b) indicated that most of energy was <5000 Hz, thus we chose a sampling frequency of 10 000 Hz with an effective bandwidth of 14 Hz.

We used the same terminology as Payne & McVay (1971) for song structure analysis. A 'unit' was defined as the shortest sound that appears continuous to the human ear (Payne & McVay, 1971). Repetition of several units of the same type constitutes a 'phrase'. A sequence of phrases makes up a 'theme'. Several themes comprise a 'song'. Successive songs can be sung without pause comprising a 'song session'.

We identified some unit types based on aural analysis and spectrographic analysis. Although contours within the same unit type varied slightly, this variation was generally small compared with those among different unit types. We categorized phrase into the same 'phrase type' when they consisted of the same unit types, and categorized themes into the same 'theme type' when they were on the same position in the songs and consisted of the same or similar phrase types. We coded unit types by using alphabetic letters, and described phrase and theme types in each song using coded unit types. The details of song structure in Ryukyu region during this period were represented in Maeda *et al.* (2000).

Previous studies considered a ratchet sound to be associated with surfacing (Winn & Winn, 1978; Tyack, 1981; Chu & Harcourt, 1986; Helweg *et al*., 1990; Cerchio, 1993). We treated the ratchet sound as one kind of unit type because we were not able to confirm the whale surfacing when ratchet sounds were produced, and found this sound occurred every year in singles or together with other unit types to make up phrases or themes. This sound was further divided into two unit types based on differences in duration (unit types Rat and Rat −).

We defined a 'full song' as a song recorded fully from beginning of first theme type to the end of the last theme type. We arbitrarily chose the theme type containing ratchet sounds as the last one of a song, and the following theme type as the first theme type of the subsequent song. Theme types following the first theme type were numbered successively. We did not identify individual whales during recording, so that information on a particular singer was not available. We analyzed nineteen full songs from each year's sample, all recorded during the same month (Table 1).

Because unit types of humpback whale song varied from acoustically simple to complex, we classified four categories based on the contours of the sound spectrogram; harmonic, amplitude modulated, impulsive and complex sounds. We defined a 'harmonic sound' as the unit type that had clear harmonics. The 'amplitude modulated sound' was defined as the unit type which had no distinct contour and consisted of amplitude modulated component in frequency. The 'impulsive sound' was defined as the unit type that was short in duration (<0.3 sec) and repeated successively at <0.3 sec intervals. The 'complex sound' was defined as the unit type which had both harmonic and amplitude modulated sounds combined.

For units of harmonic sound, we measured the following variables; duration, minimum frequency, maximum frequency, peak frequency, initial frequency, frequency at the 1/4 of duration, frequency at the 1/2 of duration, frequency at the 3/4 of duration and terminal frequency. For units of

Table 1. Details of full song sample.

Year	Date	Song duration (min:sec)	Recording location (N26°, E127°)	
1991	March 5	9:20	unknown	
	March 7	7:20	unknown	
	March 13	9:01	14.68,	12.71
1992	March 2	14:35	06.15,	06.97
	March 10	12:43	17.18,	14.66
	March 12	12:37	18.08,	14.95
1993	March 5	9:24	19.04,	06.36
	March 27	14:28	14.95,	15.70
1994	March 4	9:52	17.05,	14.98
	March 5	9:49	21.87,	03.66
	March 9	13:18	06.56,	18.63
1995	March 2	9:03	16.61,	23.76
	March 7	6:09	18.72,	12.60
	March 8	10:37	06.03,	17.14
1996	March 6	13:56	06.26,	19.36
	March 28	7:36	11.09,	13.67
1997	March 9	18:11	20.24,	02.95
	March 11	7:34	unknown	
	March 28	11:39	16.13,	17.25

amplitude modulated and impulsive sounds, we measured only four variables of duration, minimum frequency, maximum frequency and peak frequency, and failed to measure the remaining variables. This is because units of amplitude modulated sound had no distinct contour and units of impulsive sound were very short in duration. These variables were measured directly on the computer display using the cursor. To see acoustic characteristics in Ryukyu region, we also measured peak frequency of ambient noise in this region.

Most of variables did not meet the assumption of normal distribution, so that we attempted power or log transformations. After transformation, principal component analysis was conducted for each category. Principal component analysis in all cases was calculated from a correlation matrix of all variables.

Results

A total of 4681 units from humpback whale songs were obtained from 1991 to 1997. Units ranged from 29 to 4795 Hz and 0.1 to 14.3 sec, which were similar to the results of previous studies in the other regions (30 to 4000 Hz, 0.2 to 8.0 sec for Bermuda song: Payne & Payne, 1985; 50 to 8000 Hz, 0.1 to 5.7 sec for Australian song: Mednis, 1991). Peak frequency of units ranged from 55 to 4879 Hz. Peak frequency of ambient noise in the Ryukyu region varied by weather condition and recording location, ranging from 29 to 156 Hz. The majority of song units (83.7%) were higher than the range of peak frequency in ambient noise.

Thirty-two unit types were identified based on aural and spectrographic analysis (Fig. 1). We classified these unit types into four categories; twenty unit types (A, A −, A+, B, D, E, F, Fj, G, J, L, M, N, P, S, T, Tj, V, W, and Y) were classified as harmonic sounds, eight (C, H, O, Q, Z, Z+, Rat, and Rat −) as amplitude modulated sounds, three (K, R, and X) as impulsive sounds, and one (Hj) as a complex sound. Table 2 presents the acoustic characteristics of each unit type.

Unit groups based on PCA patterns

To explore the relationship among unit types and to group similar unit types, principal component analysis was conducted for three data sets of harmonic, amplitude modulated, and impulsive sounds. Complex sound was not subject to PCA because we found only one unit type in this category.

For harmonic and amplitude modulated sounds, eigenvalues of the first two factors were higher than 1.00, and these first two factors explained more than 80% of the variance (Table 3). For impulsive sound, only eigenvalue of the first factor was higher than 1.00, and the first factor explained at 75.8% of the variance (Table 3). For harmonic sound, most of variables associated with frequency were heavily weighted on factor 1, and duration was most heavily weighted on factor 2 (Table 3). A similar tendency was found for amplitude modulated sound (Table 3). For impulsive sound, all three variables, except for duration was heavily weighted on factor 1 (Table 3).

Based on PCA patterns, we divided sounds visually into four unit groups (H_1–H_4) for harmonic sound, two unit groups (A_1–A_2) for amplitude modulated sound, and three unit groups (I_1–I_3) for impulsive sound (Figs. 2a–c). Within a unit group, no clear boundary among unit types was found.

For harmonic sound, H_1 (unit types A, A+, A −, B, D, F, G, M, N, S, T, Tj, V and W) was the group that had less frequency modulation and relatively long duration compared to the other three groups in this category. Although unit types Tj, S and V had rapid frequency modulation, most unit types of H_1 started and ended at low frequency. H_2 (unit type Y) started and ended at high frequency, and often had several 'loops' in unit contour. Both H_3 (unit types J and P) and H_4 (unit types E, Fj and L) were a rapid upsweep and short in duration. The difference between H_3 and H_4 was initial frequency. Unit types of H_3 started at higher frequency than those of H_4. For amplitude modulated sound, there were differences in all variables except for duration between two unit groups. A_1 was lower in minimum, maximum and peak frequency than A_2. For

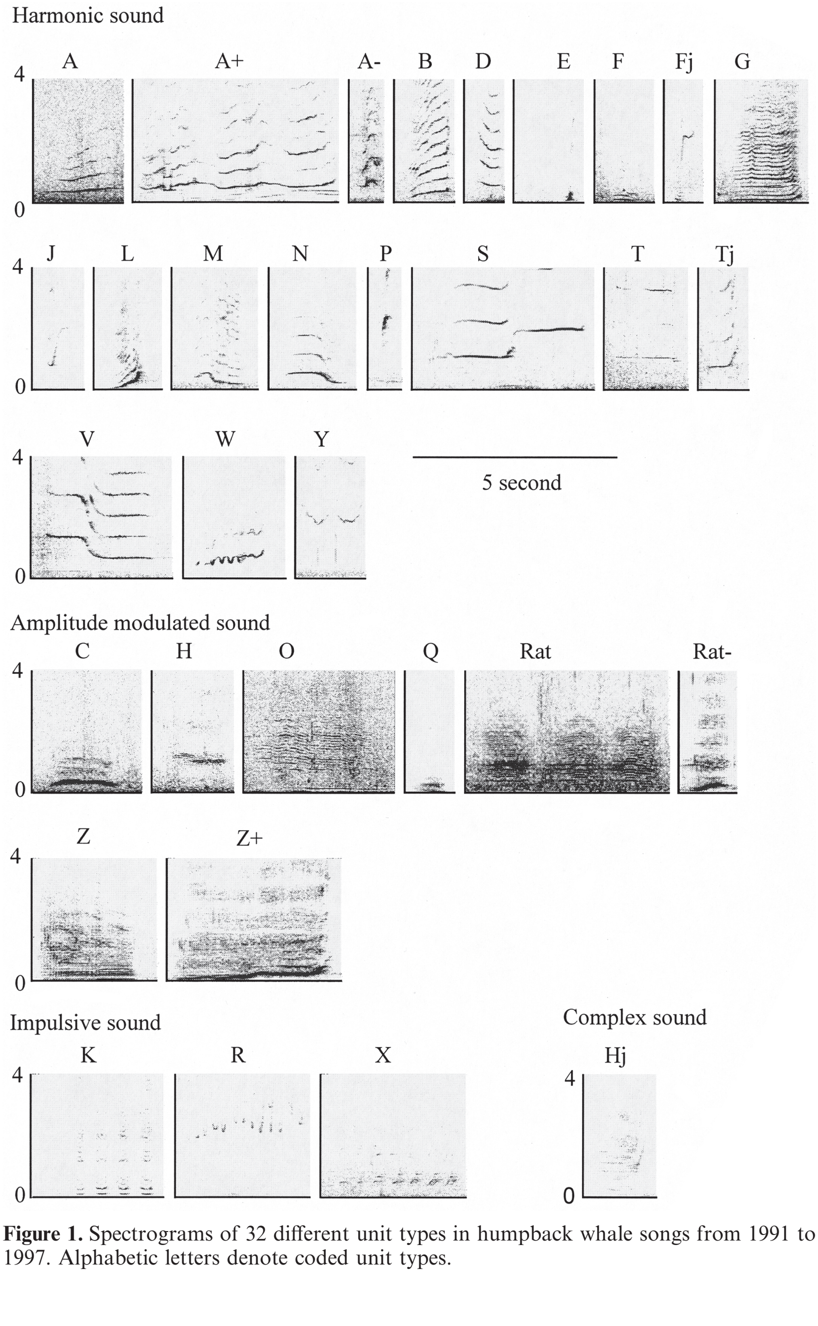

Figure 1. Spectrograms of 32 different unit types in humpback whale songs from 1991 to 1997. Alphabetic letters denote coded unit types.

impulsive sound, three unit types differed in the height of minimum, maximum and peak frequency.

Occurrence of each unit group within song

Table 4 represents the occurrence of each unit group in different theme types of humpback whale songs during seven years. Some unit groups occurred in more theme types than others. Unit groups H_1, H_4 and A_2 occurred during seven years, which were found in 34 (65.4%), 18 (34.6%) and 25 (48.1%) of the 52 theme types, respectively. One or some of these three unit groups were found in all theme types but one (the fifth theme type of 1996).

Table 2. Mean and SD of acoustic characteristics of each humpback whale song unit type from the Ryuku region, Japan.

		Duration		Minimum freq		Maximum freq		Peak freq		Initial freq		Freq at 1/4		Freq at 1/2		Freq at 3/4		Terminal freq	
Unit type	n	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Harmonic sounds																			
A	479	1.8	0.7	316	107	465	172	381	129	351	137	378	128	384	128	393	135	425	170
A −	49	0.8	0.4	388	104	699	186	566	220	393	101	484	110	554	123	599	141	684	189
A+	24	5.5	2.5	305	92	476	203	382	159	296	95	392	152	408	149	405	165	435	204
B	399	1.2	0.4	222	70	423	143	352	194	229	81	268	79	310	92	349	114	415	147
D	45	0.7	0.2	514	45	638	104	565	75	618	120	580	71	564	65	564	61	558	95
E	106	0.5	0.1	136	36	3171	691	388	414	136	36	282	199	1020	628	2197	418	3171	691
F	146	0.8	0.2	101	32	164	45	137	25	101	32	135	24	130	22	122	27	164	45
Fj	34	1.2	0.5	122	61	1574	327	842	586	122	61	276	294	1367	335	1379	322	1475	293
G	179	1.7	0.8	138	22	321	64	199	115	138	22	154	30	197	42	249	59	321	64
J	107	0.8	0.3	661	245	2600	578	870	471	661	245	851	306	1262	480	1640	607	2600	578
L	707	0.6	0.2	165	92	872	261	341	214	180	119	260	133	386	165	536	194	826	260
M	163	1.3	0.4	244	40	680	129	381	231	558	99	607	134	399	60	324	39	244	40
N	125	1.4	0.5	317	71	753	157	570	141	432	143	525	99	626	148	604	196	527	257
P	244	0.2	0.1	1409	750	2254	838	1789	927	1409	750	1570	779	1725	778	1891	790	2254	838
S	84	3.2	0.4	499	65	1030	142	651	164	553	184	575	59	783	132	940	170	944	280
T	43	1.2	0.3	852	267	938	271	843	280	871	278	899	260	882	257	899	264	935	274
Tj	12	1.4	0.3	755	84	1324	324	744	428	781	88	835	87	815	56	918	86	1324	324
V	33	3.2	0.8	497	237	1235	247	523	278	1048	224	1157	255	644	210	522	248	509	231
W	24	1.9	0.4	422	33	781	90	548	35	422	33	511	39	537	41	575	45	781	90
Y	49	1.0	0.7	2103	448	2924	633	2424	622	2306	553	2350	445	2321	475	2480	435	2790	673
Amplitude modulated sounds																			
C	59	2.0	1.1	246	44	453	91	362	55										
H	119	0.9	0.3	719	100	992	229	896	266										
O	8	2.9	0.8	172	34	250	69	348	272										
Q	324	0.8	0.4	94	69	340	207	234	293										
Rat	106	4.8	2.7	131	94	654	378	370	293										
Rat −	40	0.6	0.1	84	26	436	112	224	63										
Z	183	1.5	0.8	104	40	257	223	259	249										
Z+	30	3.2	0.6	121	32	620	84	363	52										
Impulsive sounds																			
K	152	0.2	0.1	144	68	205	98	241	166										
R	209	0.1	0.0	1183	834	1429	1014	1318	902										
X	361	0.2	0.1	356	86	514	136	690	686										
Complex sound																			
Hj	38	1.0	0.2	680	131	2148	277	1260	443										

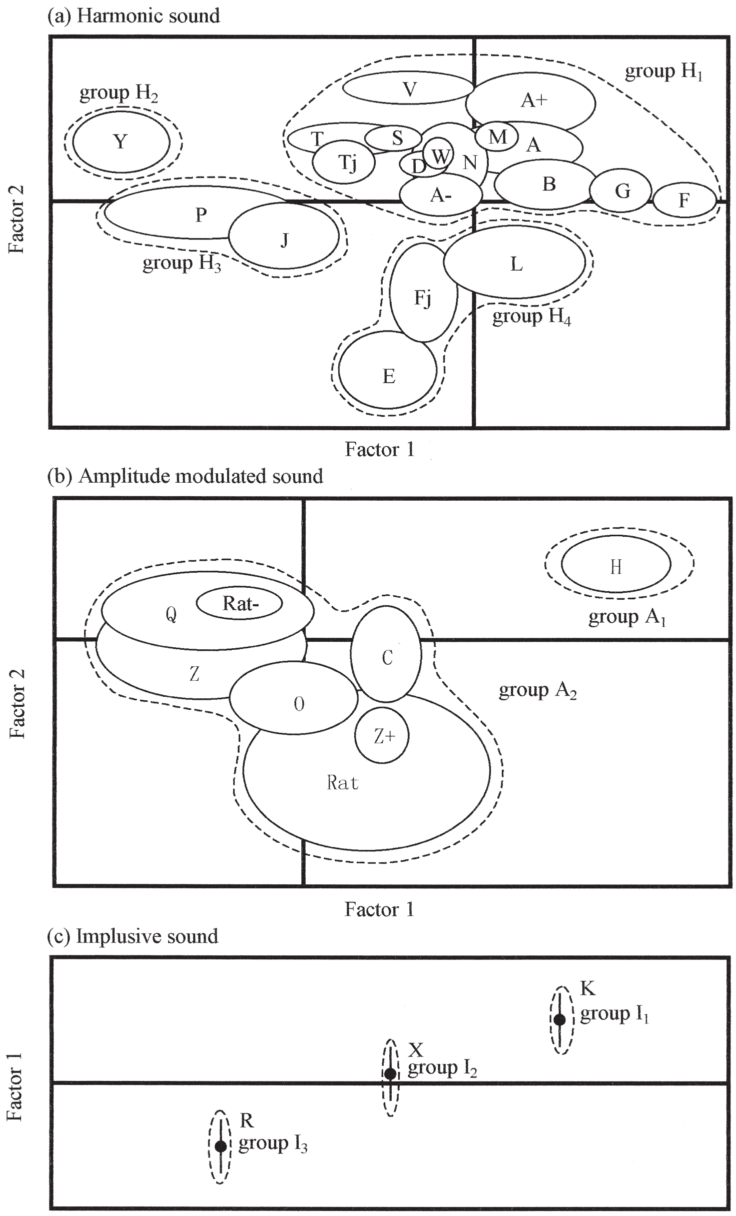

Figure 2. Occurrence pattern of unit types based on PCA for: (a) harmonic sound, (b) amplitude modulated sound, and (c) impulsive sound. Alphabetic letters denote coded unit types, and solid circles denote ± 1 SD around average in factors 1 and 2 of each unit type. Broken lines denote the borders between sound types.

While, C_1 was found in only one theme type of 1992 (1.9%).

The number of unit groups occurred in each theme type varied (Table 4). Only one unit group was found in the first and last theme types all year's songs but in 1997 when the last theme type contained two unit groups (H_1 and A_2). While, the other theme types contained one to five unit groups.

Table 3. Factor loadings for the acoustic variables, their eigenvalues, and their percent variance explained by each variable in the three categories.

Category	Variables	Factor 1	Factor 2	Factor 3
Harmonic sounds	Duration	0.34	**0.68**	**0.65**
	Minimum frequency	− **0.87**	0.40	− 0.15
	Maximum frequency	− **0.87**	− 0.38	0.22
	Peak frequency	− **0.88**	0.20	− 0.09
	Initial frequency	− **0.83**	0.49	− 0.15
	Frequency at 1/4	− **0.89**	0.37	− 0.11
	Frequency at 1/2	− **0.96**	− 0.02	0.10
	Frequency at 3/4	− **0.91**	− 0.30	0.20
	Terminal frequency	− **0.82**	− 0.49	0.21
	Eigenvalues	6.3	1.5	0.6
	% variance explained	70.3	16.8	7.0
Amplitude modulated sounds	Duration	0.25	− **0.95**	0.17
	Minimum frequency	**0.85**	0.36	0.20
	Maximum frequency	**0.88**	− 0.16	− 0.44
	Peak frequency	**0.91**	0.08	0.20
	Eigenvalues	2.4	1.1	0.3
	% variance explained	59.5	26.6	7.5
Impulsive sounds	Duration	0.48	**0.87**	0.01
	Minimum frequency	− **0.98**	0.13	− 0.10
	Maximum frequency	− **0.96**	0.19	− 0.16
	Peak frequency	− **0.96**	0.11	0.28
	Eigenvalues	3.0	0.8	0.1
	% variance explained	75.8	20.9	2.7

Bold values indicate significant loadings.

Discussion

The majority of units (83.7%) were higher in peak frequency than the range of ambient noise in Ryukyu region (29 to 156 Hz). A similar tendency was reported in the calls of bowhead whale, *Balaena mysticetus* (Clark & Johnson, 1984) and southern right whale, *Eubalaena australis* (Clark, 1982). Clark (1982) documented that the major type of call in right whales coincided with the low energy band in the ambient noise, and suggested that the calls have been under selective force from environment condition. Therefore, units of humpback whales appear to have been influenced by ambient noise in that they increased in frequency to avoid the lower ambient noise.

Humpback whales produced a variety of units, ranging from short harmonic units to long amplitude modulated units such as the ratchet. Thirty-two unit types were recognized in humpback whale songs over seven years, which were grouped into four categories based on the contour of spectrograms; harmonic, amplitude modulated, impulsive and complex sounds. Mednis (1991) recognized fifteen unit types from the 1988 Australian song, and grouped unit types into four categories; harmonic, broad band with spectral line, broadband impulsive and complex sounds (he used the term ‘sound type’, not ‘unit type’). There were several differences in definition of category between Mednis (1991) and this study. Amplitude modulated sound reported here was similar to ‘broadband with spectral line’ described by Mednis (1991). However, we referred to amplitude modulated sound because unit types in this category usually had no harmonics. ‘Broadband with spectral line’ described by Mednis (1991) contained the sound that was combination of harmonic sound and amplitude modulated sounds, while we referred such sound as complex sound. ‘Broadband impulsive’ described by Mednis (1991) and impulsive sound reported here had a similar temporal pattern. However, we referred to impulsive sound because this sound was not a broadband sound and had often harmonics in our samples. The complex sound reported herein had harmonics and an amplitude modulated sounds combined, while that described by Mednis (1991) was the sound that

Table 4. Occurrence of each humpback whale sound group in different song theme types during seven years.

Theme type	Harmonic							Amplitude modulated							Impulsive							Complex
	1991	1992	1993	1994	1995	1996	1997	1991	1992	1993	1994	1995	1996	1997	1991	1992	1993	1994	1995	1996	1997	1992
1st	H_1	H_1	H_1	H_1	H_1	H_1	H_1															
2nd	H_1	H_1	H_1	H_1	H_1	H_1											I_2	I_2	I_2	I_2		
						H_3	H_3															
	H_4						H_4															
3rd	H_1	H_1	H_1	H_1		H_1	H_1	A_2	A_2	A_2												
						H_3	H_3															
	H_4			H_4	H_4																	
4th	H_1	H_1	H_1	H_1	H_1		H_1		A_2	A_2					I_1		I_1					
				H_2																		
					H_3	H_3																
		H_4	H_4	H_4	H_4	H_4																
5th							H_1	A_2	A_2					A_2			I_1	I_1	I_1	I_1		
					H_3												I_3	I_3	I_3	I_3		
	H_4	H_4	H_4	H_4	H_4																	
6th		H_1		H_1	H_1	H_1	H_1	A_1	A_1								C1					
	H_3	H_3						A_2	A_2	A_2	A_2	A_2	A_2	A_2								
			H_4	H_4	H_4																	
7th				H_1	H_1	H_1				A_1	A_1											
								A_2	A_2	A_2	A_2	A_2	A_2									
8th										A_2	A_2	A_2	A_2									

harmonic and impulsive sounds combined. A 'unit' was defined as the shortest sound that appears continuous to the human ear (Payne & McVay, 1971). Judging from sound spectrograms, complex sound in Mednis (1991) seems not to be one continuous sound.

Although Mednis (1991) illustrated only eight spectrograms out of fifteen unit types, inspection of individual unit types' spectrograms revealed that most Australian unit types were similar to those reported herein. For example, the 'moan' and the 'cry' described by Mednis (1991) are very similar to unit types A and B, respectively. 'Moan staccato' and the 'whoomp' were described by Mednis (1991) as a combination of harmonic and impulsive sounds. The impulsive part of the sound was similar to unit type X reported herein. The 'chain saw growl' and the 'n-chung' described by Mednis (1991) are similar to unit types Ratchet and L reported here, respectively. Only the 'screal' of eight spectrograms were not found in our samples.

Based on PCA pattern, nine unit groups were identified from three categories. Some unit groups occurred more often than others. H_1, H_4 and A_2 were found throughout seven years; one or some of which occurred in all but one theme types. Most types of H_1 were slightly frequency modulated sound and those of H_4 were rapid upsweep sounds. Unit types of A_2 were low frequency broadband sounds. Most unit types of these three unit groups were relatively low frequency at the peak, but were not consistent with the range of peak frequencies of ambient noise, indicating that these attenuate less rapidly than higher frequency sound. High occurrence of these unit groups throughout the song appears to increase the possibility that the song message is correctly received over long distance.

Additionally, rapid upsweep sound, such as H_3 and H_4, or amplitude modulated sound, such as A_1 and A_2, also provide more clues for sound localization than less frequency modulated sound. Although the function of songs remains unknown, observation from previous studies suggested a role in attracting female mates (Winn & Winn, 1978; Tyack, 1981) or in spacing among competing males (Winn & Winn, 1978; Tyack, 1981; Helweg *et al.*, 1992). In any case, it seems to be important for whales listening to the song to locate a singer. These unit groups also could serve a possible function as locating singer.

Three unit groups of impulsive sound (I_1, I_2, and I_3), one unit group of harmonic sound (H_2) and one unit group of complex sound (C_1) were not observed in songs from any year. Perhaps these could be less important than certain groups that occurred more often in a song. Sound characteristics of these unit group appeared less detectable than other unit groups. We do not know why humpback whales used these unit groups. Winn & Winn (1978) and Payne & Payne (1985) suggested that complexity and variety of sounds in humpback whale songs is an adaptation to prevent habituation. Therefore, these may function as avoidance of monotony. Interestingly, impulsive sounds were produced in series with short intervals (<0.3 sec). Repetition could increase the efficiency of detecting these sounds against ambient noise.

Throughout seven years, the number of unit groups in the first and last theme types were small (one or two), while that of unit groups in the other theme types varied from one to five. We do not know why humpback whales construct their songs in such a way. There could be a possible relationship between the behavior of humpback whales and song structure. Previous studies reported that singing whale surfaced after ratchet sounds (Winn & Winn, 1978; Tyack, 1981; Chu & Harcourt, 1986; Helweg *et al.*, 1990; Cerchio, 1993), although we were not able to confirm this. If true, we speculate that a whale surfaces during the last theme type that contained ratchet sound and dives diving during the first theme type. Sound attenuation occurs rapidly as a singer surfaces. If singer produce a variety of sounds near the surface, many of these may not transmit over a long distance. Interestingly, near the surface singers often produced H_1 and A_2, the characteristics of which transmit over a long distance compared to the other unit groups.

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