A classification and comparison of vocalizations of captive killer whales (*Orcinus orca*)

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An acoustical study was conducted on captive killer whales (*Orcinus orca*) to determine if individuals or groups differed in their vocalizations. Twenty-one different underwater vocalization categories produced by 13 animals were recorded within a 40 Hz to 20 kHz bandwidth. Eight acoustical variables (starting and ending frequencies of the signal, duration, harmonic interval, starting and ending frequencies of the fundamentals, and low and high concentration of energy) were measured for each vocalization. MULTIVARIATE DISCRIMINANT analysis was used to determine whether individual, oceanarium, or sexual differences were detectable in their vocalizations. Results showed distinct acoustical groupings by individuals, by oceanariums, and by sex.

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INTRODUCTION

Grieg (1906) contributed one of the earliest published reports on killer whale sounds, noting the flutelike calls from young animals and roars from old bulls during whaling operations. Valdez (1961) recorded, but did not extensively analyze, ultrasonic sounds made by these animals in the eastern Atlantic Ocean. Schevill and Watkins (1966) analyzed calls from a young captive male in British Columbia, noting clicks believed to be used in echolocation and screams assumed to be for communication. Much other work has since been conducted on this species' sounds (Hindsmann *et al.*, 1966; Singleton and Poulter, 1967; Steiner *et al.*, 1979).

The present acoustical study was conducted on captive killer whales, *Orcinus orca* L., 1758, to test the hypothesis that individual whales can be identified by their sounds. If animals at different oceanariums and of similar sex are acoustically separable, wild *Orcinus* individuals and pods may also be acoustically distinguishable.

I. MATERIALS AND METHODS

Underwater recordings were collected from 13 captive killer whales, *Orcinus orca*, maintained at five west coast oceanariums: Sea World, San Diego, CA, five animals; Marineland, Palos Verdes, CA, three animals; Marineworld, Redwood City, CA, two animals; Vancouver Public Aquarium, Vancouver, British Columbia, Canada, two animals; and Sealand, Victoria, British Columbia, Canada, one animal.

Prior investigations by the senior author indicated that sound production in captivity by *Orcinus* was diurnally variable so recordings were not made at fixed times. With the exception of the Sea World recordings, all underwater sounds were recorded with a Celesco LC–10 hydrophone and a Nakamichi 550 cassette tape recorder.[1] At Sea World, A Wilcoxon hydrophone and a Uher 4400 reel-to-reel tape recorder[1] was used. The frequency response of both systems (40 Hz to 19 kHz) was limited by the tape recorders. Our previous recordings and a review of the literature showed peak energy in the signals of *O. orca* to be below 20 kHz, indicating that the above systems were adequate for the proposed research. Both recorders had two channels. Data were recorded on one channel and simultaneous commentary recorded on the other. The identity of the particular animal making the sound was determined by noting bubble emission from the blowhole or by the location of the whale relative to the hydrophone. Also, data on sex, oceanarium location, and geographical area of capture were noted for each whale.

Onomatopoeic sound types were established and examples of each sound type were selected for each animal. A "waterfall" spectrogram of each working tape was made with a Spectral Dynamics model 301 real-time spectrum analyzer,[1] sampling 40 ms of sound between 0 and 10 kHz sequentially every 50 ms. Pulses occurring faster than the time per line were resolved from the harmonic interval of pulse sideband. Due to the sampling rate of the analysis equipment, pulse-repetition rates of signals, without obvious harmonic structures, could not be resolved. Effective filter

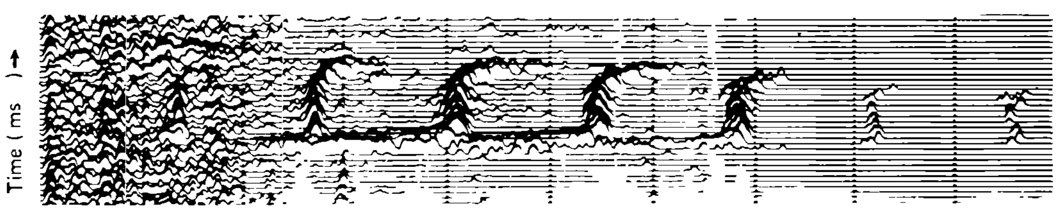

FIG. 1. Sample spectrogram of an upscream (50 ms per line).

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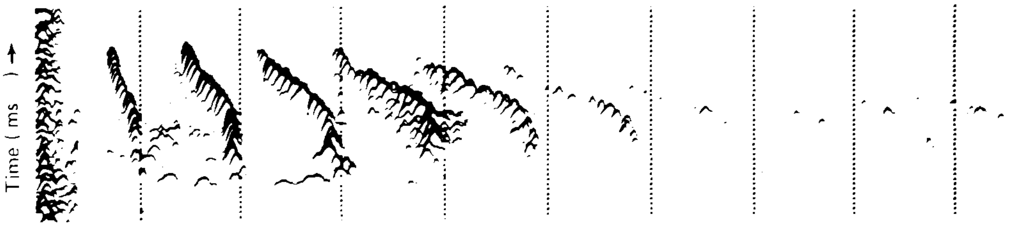

FIG. 2. Sample spectrogram of a downscream (50 ms per line).

bandwidth was 19.5 kHz.

When necessary, sonograms were made with a Kay Elemetrics Corporation, model 7029A, sound spectrograph.[1]

Eight acoustical variables for each sound were measured directly from the spectrograms: minimum frequency (lowest frequency observed); maximum frequency (highest frequency observed); duration (time period of the signal); starting frequency of the fundamental; ending frequency of the fundamental; and the frequency interval between harmonics. For sounds with obvious harmonic structure, the beginning and ending frequency of the stressed harmonic was included. Alternatively, if a vocalization was more broadband, with less obvious harmonic structure, the beginning and ending frequency of the "stressed" area in the signal (stressed areas appear darker on the spectrogram display) was included.

For statistical analysis the STATISTICAL PACKAGE FOR THE SOCIAL SCIENCES (SPSS) was used and subprogram AGGREGATE calculated means, standard deviations, and maximum and minimum values for each sound type for each animal (Nie *et al.*, 1975). All repetitions of each sound type from each animal were grouped together and a grand mean, standard deviation, and maximum and minimum values were calculated for each sound variable.

The MULTIVARIATE DISCRIMINANT analysis program tested for interindividual, intergroup, and sexual differences in vocalizations. These discriminating functions had the form

$$D_i = d_{i1} z_1 + d_{i2} z_2 + \cdots + d_{ip} z_p,$$

where D_i was the score of the discriminant function i, the d's were weighting coefficients, and the Z's were the standardized values of the p discriminating variables used in the analysis. Details of the mathematical derivation of this procedure can be found in Cooley and Lohnes (1971) and Tatsuoka (1971). In the direct method, the eight acoustical variables were entered into the analysis concurrently. The discriminant functions were created directly from the entire set of variables. In the stepwise method, the variables were selected for entry in order of their discriminating power using the Rao's V method for the selection of the variables to be included in the discriminant (Nie *et al.*, 1975). A variable was included only if its partial multivariate F ratio was larger than a specified value (= 1.0).

II. RESULTS

A. Sound types

We classified the different sounds produced by the captive killer whales into 21 different types. Some whales produced all 21 sound types; however, 11 appeared with greater frequency than the others. All the sounds were readily assigned by ear to a particular type and could be identified consistently by other people even though spectrograms revealed considerable variation within each sound type. The 11 major sound types are listed and described below. The

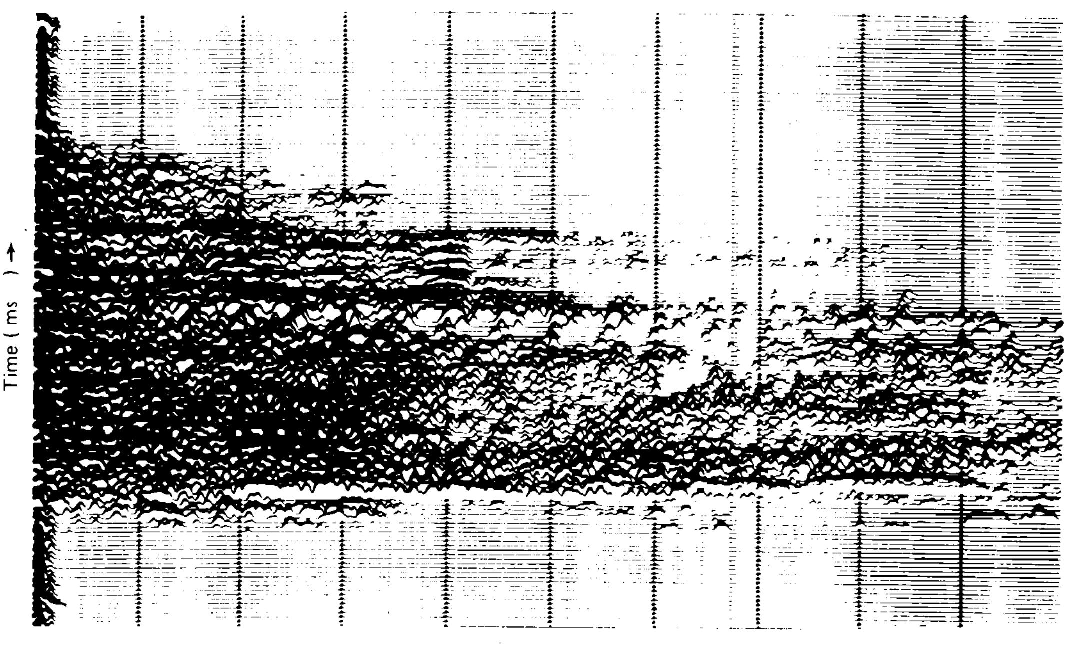

FIG. 3. Sample spectrogram of a creak (50 ms per line).

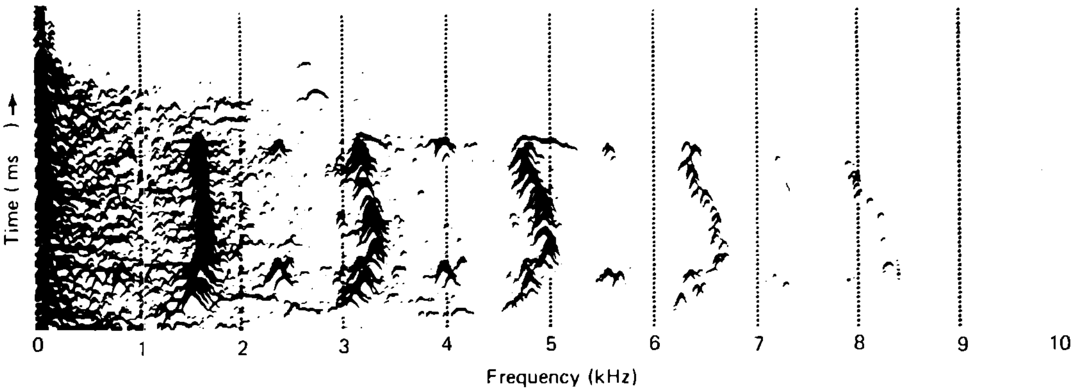

FIG. 4. Sample spectrogram of a whine (50 ms per line).

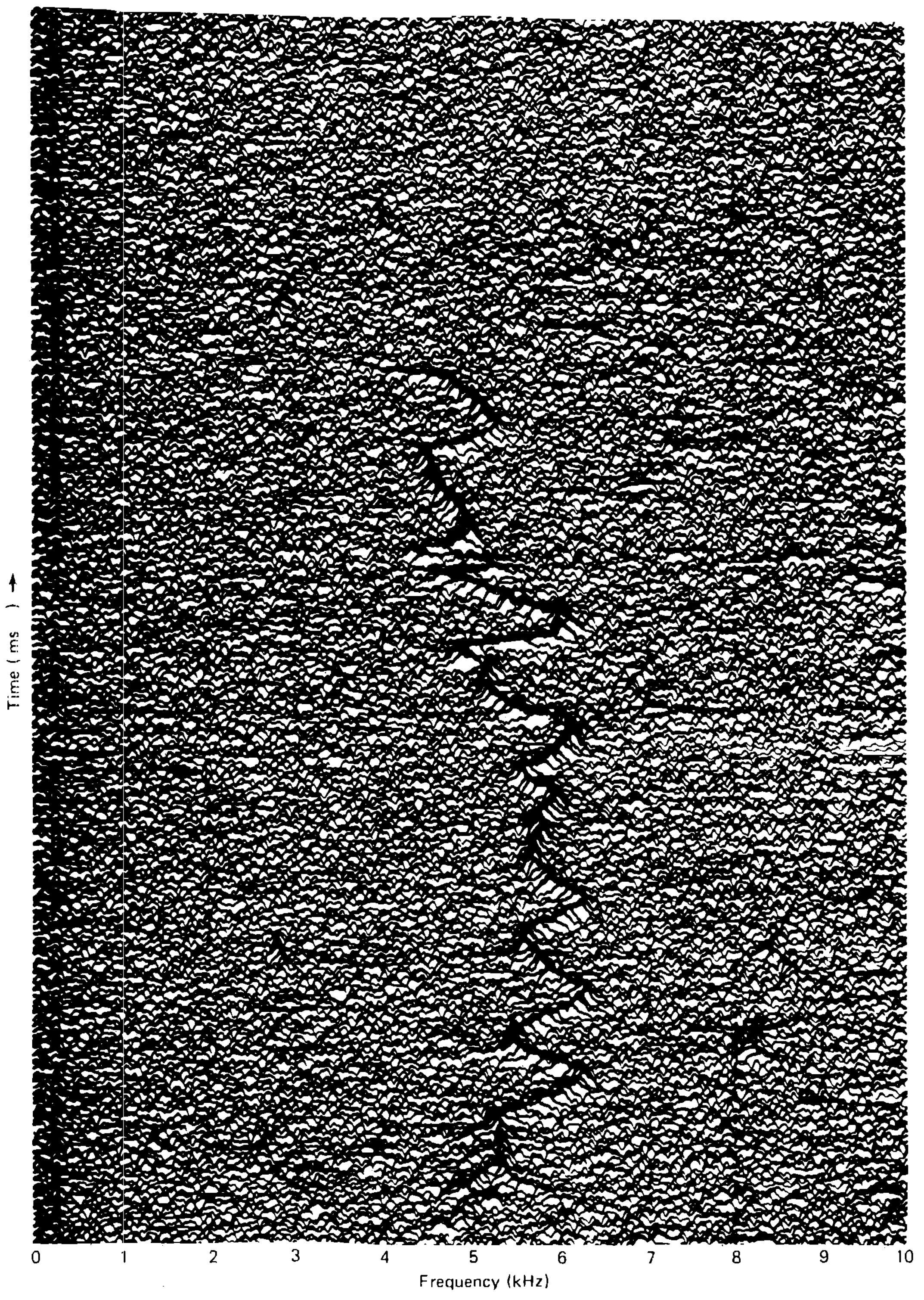

FIG. 5. Sample spectrogram of a whistle (50 ms per line).

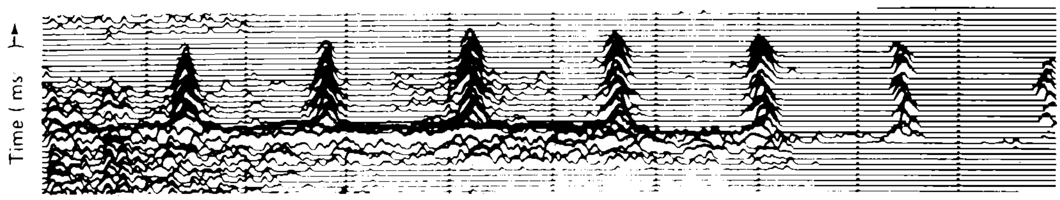

FIG. 6. Sample spectrogram of a tone (50 ms per line).

values reported for each sound type represent averages from the records of all animals.

1. Upscream

Upscreams (Fig. 1) were upward sweeps in frequency with time. The average call duration was 973 ms. These sounds typically began with a rapid burst of broadband pulses. This pulse rate then decreased and a harmonic structure emerged. Mean starting and ending frequencies of the fundamental were 1220 and 1865 Hz, respectively. The pulse repetition rate, derived from the harmonic interval, averaged 1050 per second. Upscreams always contained several strong harmonics. The second or third harmonic was usually stressed. Upscreams were recorded from 11 animals, with 1100 usable records.

2. Downscream

Downscreams (Fig. 2) were downward sweeps in frequency with time and usually started at a slightly higher frequency than upscreams. Several strong harmonics were evident. Average fundamental frequencies began at 1495 Hz and ended at 1020 Hz. The average duration was 1011 ms. A mean pulse repetition rate of 886 per second was calculated from the harmonic interval. Most of the energy was in the second, third, and fourth harmonics. Downscreams ($n = 1200$) were recorded from 12 whales.

3. Creak

Creaks were characterized by a rapid series of broadband pulses with energy distributed between 570 and 7160 Hz, but concentrated between 1390 and 4068 Hz (Fig. 3). Creaks averaged 2.3 s in duration. Pulse repetition rate could not be determined from the spectrograms due to the sampling rate of the analysis equipment. Therefore these modulation rates probably fell within the uncertainty window of the equipment, which we estimate to be somewhere between 10 and 100 Hz. Creaks were heard most often from Sea World's animals and were also heard at Sealand and from one animal at Marineworld. A total of 300 creaks were analyzed.

4. Whine

Whines did not exhibit the sweeps in frequency as did upscreams and downscreams. A slight overall rise ($\bar{x} = 5$ Hz) in frequency with time was measured (Fig. 4). The variable frequency modulation within the whine was not included in the analysis. The average starting fundamental frequency of 1435 Hz was slightly higher than that of the upscream, but the ending frequency of the fundamental was only 1470 Hz. Duration averaged 1.2 s. The average pulse-repetition rate was 1200 per second. Maximum energy was concentrated between 3450 and 4417 Hz. Three-hundred whines were recorded from six animals.

5. Whistle

Whistles were the only phonations that were not composed of pulse-modulated signals (Fig. 5). The frequency range was higher than in the other sound types with a mean minimum frequency of 4268 Hz and a mean maximum frequency of 6608 Hz. The overall average frequency was 5000 Hz. Whistle duration averaged 2.3 s, which was longer than other sound types investigated. Seven animals produced 200 whistles.

6. Tones

This pulse-modulated sound was distinguished from upscream, downscreams, and whines by much less frequency modulation (Fig. 6). The average fundamental began and ended at 1344 Hz. The mean modulation frequency was 1072 Hz. Duration averaged 1.5 s. Typically, the second or third harmonic was stressed. Three-hundred fifty tones were recorded from seven whales.

7. Buzz

Typical buzzes were short, averaging 658 ms (Fig. 7). The average energy bandwidth of buzzes contained frequencies between 1390 and 9136 Hz, but most energy was concentrated between 3000 and 6150 Hz. The high pulse repetition rate could not be determined from the spectrograms. Seven whales produced 350 buzzes.

8. Ricochet

This unusual term for a sound type resulted from its unmistakable resemblance to a ricocheting bullet. To the human ear, a ricochet gave the impression of being a composite of two sounds (Fig. 8). The average ricochet contained ener-

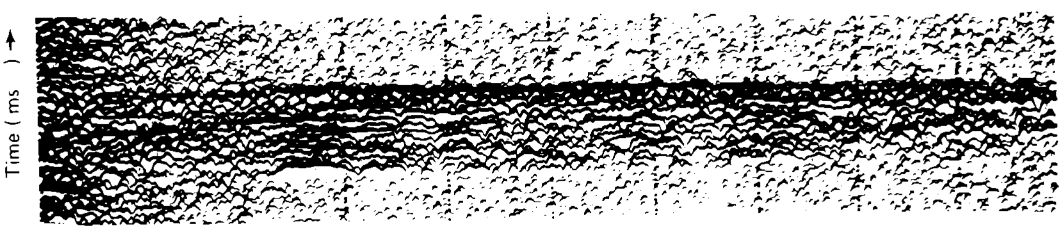

FIG. 7. Sample spectrogram of a buzz (50 ms per line).

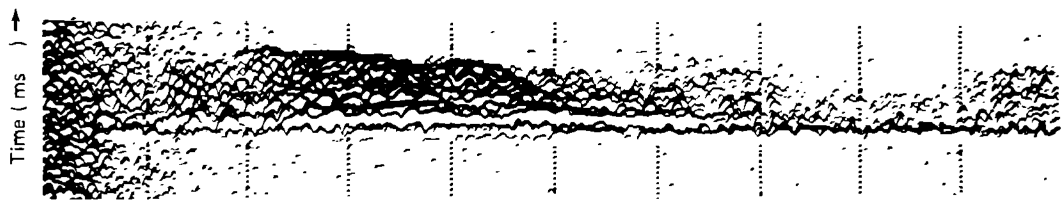

FIG. 8. Sample spectrogram of a ricochet (50 ms per line).

gy between 1550 and 7647 Hz. Most energy appeared to be between 2985 and 4970 Hz. Bandwidth was much wider at the beginning than at the end of a ricochet. Duration was short, averaging 703 ms. Two-hundred ricochets were recorded from four whales (Marineland and Marineworld).

9. Click burst

Click bursts were composed of a rapid and repetitive series of pulses (Fig. 9). The average duration of a series of click bursts was 3.8 s. Although usually produced at a high repetition rate, at times this rate was slow enough to resolve individual pulses (3–4 per second). Click bursts contained substantial energy at frequencies as low as 100 Hz and extended above 10 kHz. Analysis with a frequency window of 0 Hz to 20 kHz resulted in considerable energy in these signals up to the limitations of our equipment (19 kHz). Click bursts were recorded from eight whales which provided a total of 400 records.

10. Chatter

Chatter also consisted of a rapid series of broadband pulses (Fig. 10). The mean minimum and maximum frequencies were 340 and 9000 Hz, respectively. Average duration was 2 s. Pulse repetition rate could not be calculated from the displays. Three-hundred chatters were recorded from six whales.

11. Seesaw

This should swept rapidly upward and then downward (Fig. 11). The mean starting frequency of the fundamental was 809 Hz and the mean ending frequency was 718 Hz. Average duration was 851 ms. Strong harmonics were evident in seesaws. The mean repetition rate, derived from the harmonic interval, was 595 per second. Typically, the second and third harmonics were stressed. Seesaws were recorded from three animals at Sea World, with a total of 150 usable records.

B. Occurrence of two sounds emitted simultaneously

On several occasions, clicks and frequency-modulated whistles or amplitude-modulated sounds were emitted simultaneously by one individual. Clicks and whistles, slowed down eight times, are displayed in Fig. 12. Two different amplitude-modulated pulse trains apparently can be produced simultaneously as evidenced by the sonogram in Fig. 13.

C. Multivariate discriminant analysis

Comparison of similar sound types revealed significant acoustical differences among individuals. How accurately repetitions of an individual's sounds were classified (by the computer) varied with sound type, ranging from 100% for creaks to 41.3% for whistles (Table I). This is illustrated in the plots of the first two discriminant scores for individual animals for three of the major sound types (Figs. 14–16). For each sound type, some, but not all, whales were perfectly matched to all repetitions of their vocalizations (Table II). When the computer misclassified a vocalization from an individual, the misclassified sound was usually placed with an animal maintained at the same oceanarium.

Animals could be grouped acoustically by oceanarium with 47.4% (creak) to 92.7% (ricochet) accuracy, but separation of oceanarium by creaks was not statistically significant, $p > 0.05$ (Table III). A plot for downscreams by oceanarium is shown in Fig. 17. When a vocalization for a specific oceanarium was misclassified, the following pattern emerged.

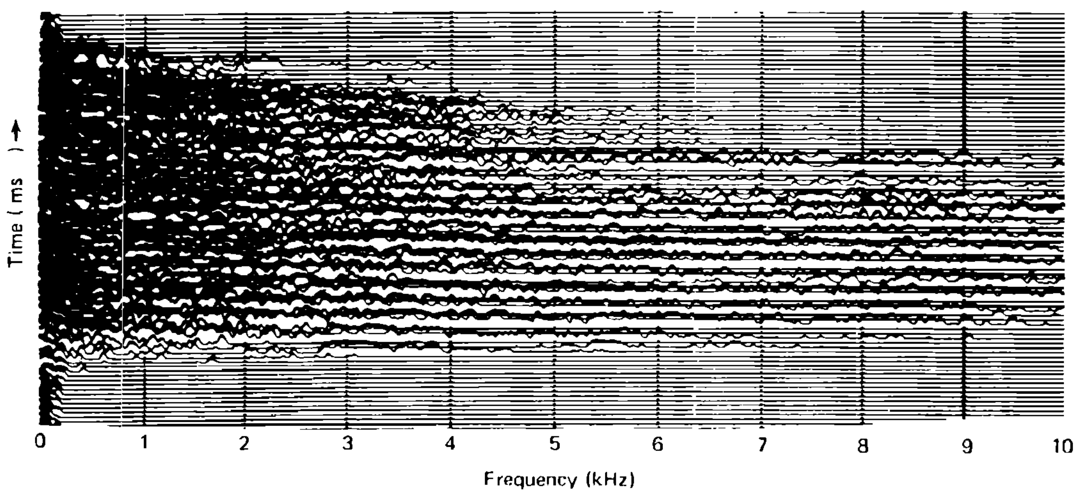

FIG. 9.Sample spectrogram of a click burst (50 ms per line).

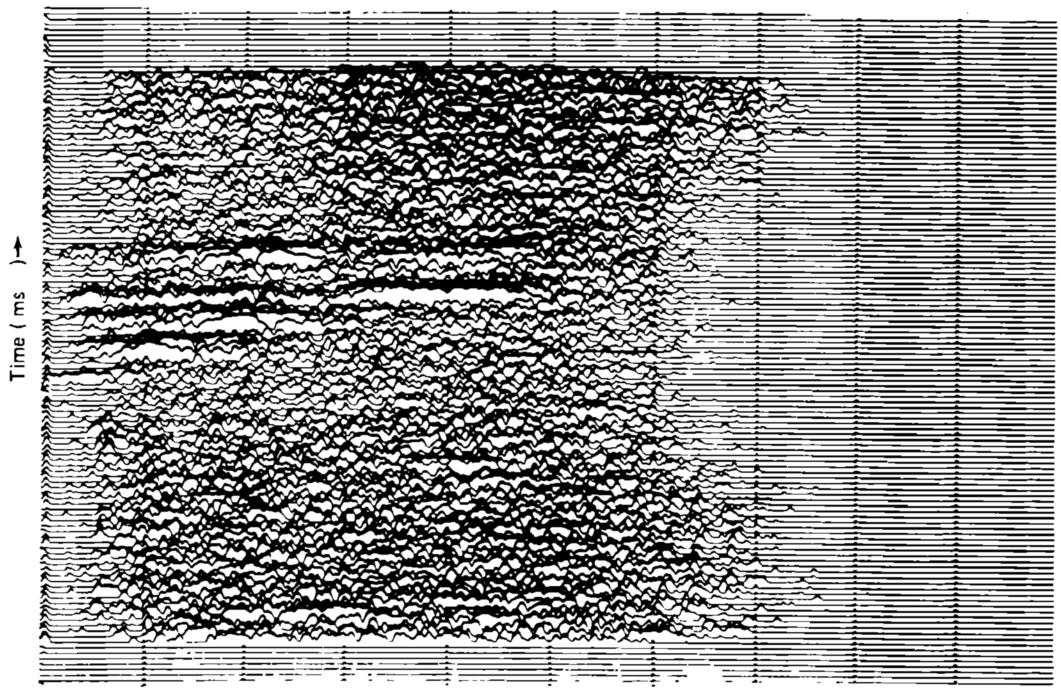

FIG. 10. Sample spectrogram of a chatter (50 ms per line).

Marineland and Marineworld tended to group, as did Sea World and Sealand. Vancouver Public Aquarium showed groupings with all oceanariums.

Ten sound types significantly separated the seven male from the six females but not by their whistles ($p = 0.649$). Table IV lists the accuracy values obtained for sexual discrimination by sound types.

III. DISCUSSION

Killer whales, *O. orca*, produce a wide range of sounds. The limited vocabulary exhibited by some of the captive animals may reflect the amount of time we spent at a specific oceanarium rather than the absence of these call types in an individual's vocal repertoire. In the recordings made of a newly born captive animal, during the 15 days between its birth and death, only seven catagories of sounds were noted, suggesting that the young of this species must learn the other calls (Dahlheim and Moore, in preparation). These seven sound types were also recorded from the parents. Some caution should be used here in interpreting these results because only one newborn whale was recorded and behavioral/medical observations indicated that this calf was not normal.

The most prevalent sound types produced by captive animals were upscreams and downscreams. In listening to tapes made in the wild by Frank Awbrey (Antarctic), Howard Winn (North Atlantic), and from Dahlheim's recordings made in Alaskan waters, varients of these screams were frequently heard. The majority of call types were composed of clicks produced at various repetition rates and amplitude modulated and/or frequency modulated tones.

The fact that the trained human ear and statistical techniques can recognize individual whales from the sounds they produce means that these whales almost certainly can recognize each other's sounds. Individual *Orcinus* can apparently be identified by most of the sounds they product but our analysis suggests that some sound types are better predictors than others. For example, the "whistle" did not appear to differentiate animals well.

When discriminant analysis misclassified an individual, the misclassified sound was usually placed with an animal maintained at the same oceanarium. Although we used extreme care to note which animal was making a sound, we might have erred occasionally. This would decrease the apparent accuracy of the technique we used for individual discrimination.

Greater acoustical differences were noted among the oceanariums than within an oceanarium. Although each oceanarium could be discriminated from the others, the close acoustical resemblances between some of these facilities are extremely significant. The geographical origin of capture for whales of Marineworld and Marineland was the same (British Columbia), as was that of Sea World's and Sealand's animals (Lower Puget Sound, WA). Vancouver

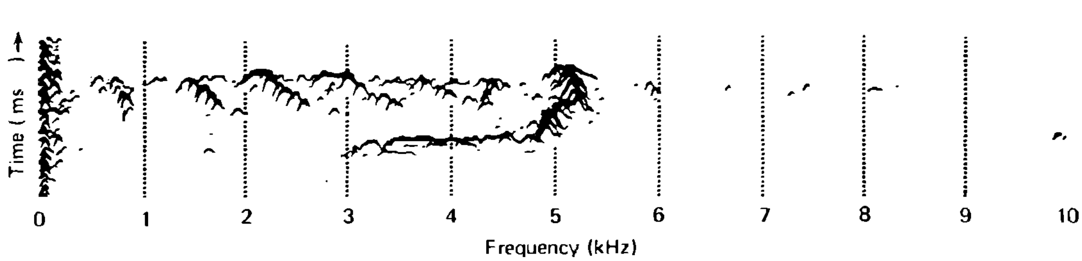

FIG. 11. Sample spectrogram of a seesaw (50 ms per line).

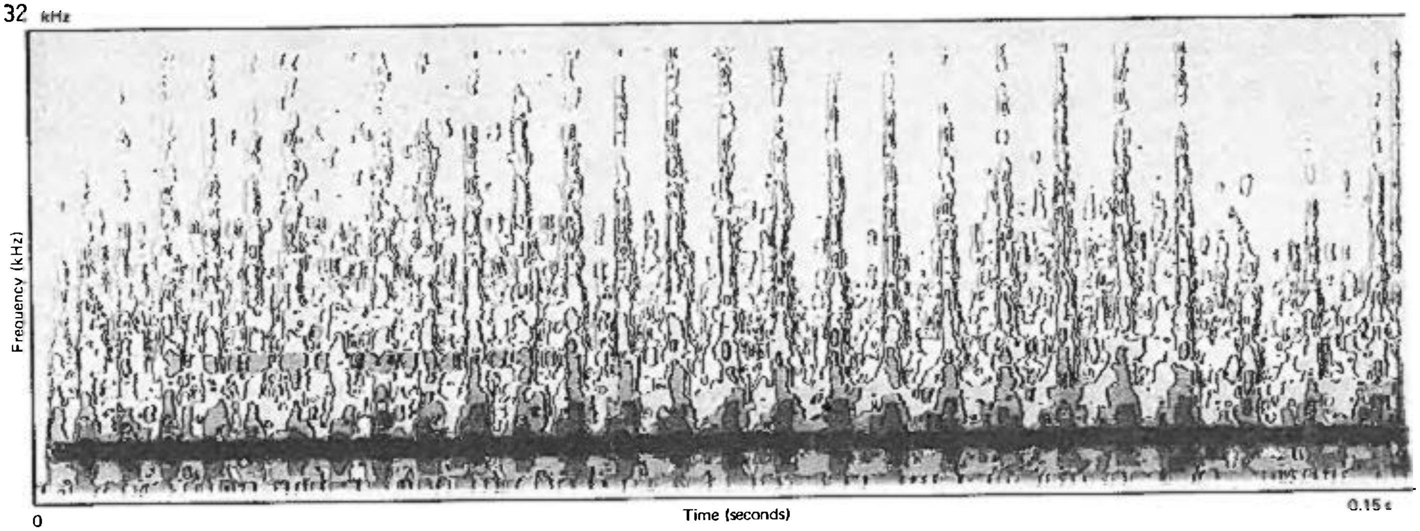

FIG. 12 Sample sonogram of a whistle and clicks emitted simultaneously.

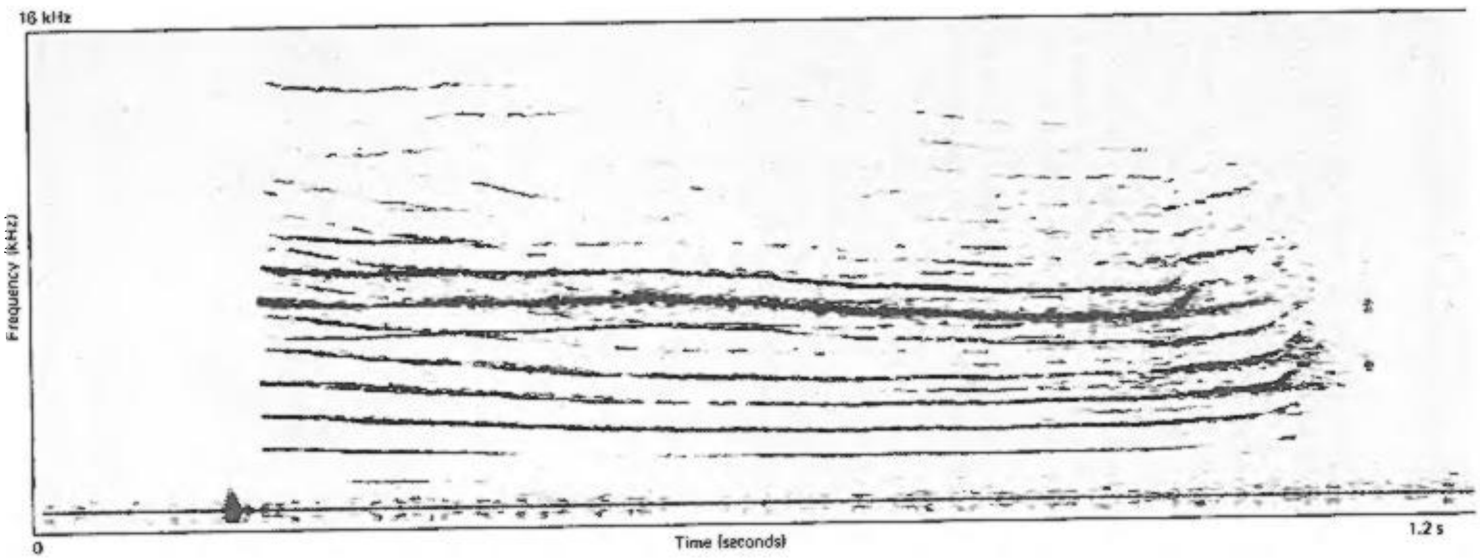

FIG. 13. Sample sonogram of two amplitude modulated signals emitted simultaneously.

TABLE I. Discrimination among individuals by sound type.

Sound type	Percent of cases correctly classified	Number of animals
Upscream	58.8	11
Downscream	64.0	12
Creak	100.0	6
Whine	93.1	6
Whistle	41.3	7
Tone	78.6	7
Buzz	88.6	7
Ricochet	85.4	4
Chatter	85.7	6
Click burst	65.5	8
Seesaw	87.9	3

Public Aquarium had animals from both regions. These results suggest dialectal differences in the calls of captive killer whales, and a maintenance of these dialects for over ten years. Dialectal differences could also help explain the grouping observed in Fig. 14. Upscreams recorded from Marineland/Marineworld animals 6, 7, A, B, and C tended to cluster. This dialectal hypothesis is further supported by the recent work of Ford (1980) who has recorded 12 different pods of free-ranging killer whales in the waters of Puget Sound, WA and British Columbia and found dialectal differences.

Sex could be discriminated by sound. These differences were not attributable to call types, but appeared to be more subtle variations. A different ordering of the eight acoustical variables for sexual separation was noted when these were compared to the ordering in individual recognition. All variables contributed to overall discrimination of sex, but again, some sound types were better sex predictors than others.

This study showed that individual, group, and sexual

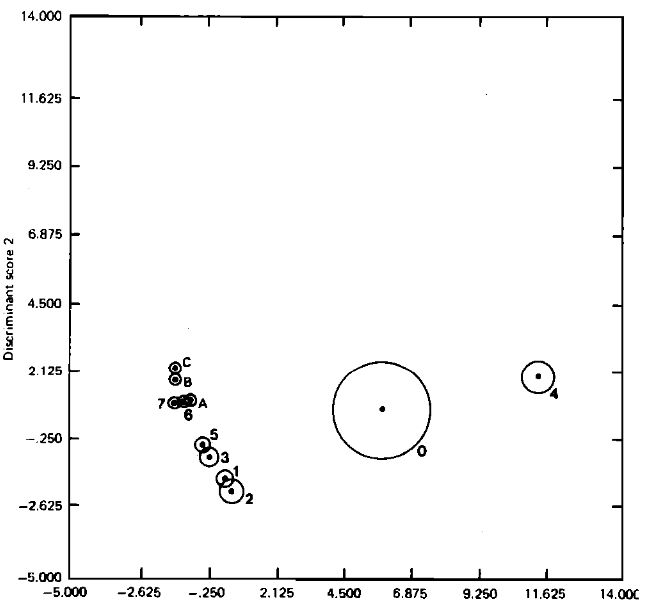

FIG. 14. Mean scores and 95% confidence circles on the first two discriminant axes for the 11 individuals producing upscreams. (Numbers/letters represent individuals.)

TABLE II. Percent of vocalization correctly classified from each individual whale based on sound type. (Oceanarium locations: Sea World = SW, Marineland = ML, Vancouver Public Aquarium = VPA, Sealand = SL, and Marineworld = MW.)

Animal number		Upscream	Downscream	Creak	Whine	Whistle	Tone	Buzz	Ricochet	Click burst	Chatter	Seesaw
1	SW	80.0	56.3	100.0	100.0	50.0	85.7	100.0	...	88.9	100.0	88.9
2	SW	90.5	75.8	100.0	...	33.7	85.7	...	...	...	...	92.2
3	SW	50.0	60.0	100.0	100.0	100.0	50.0	66.7	...	50.0	70.0	80.0
4	SW	87.5	...	...	...	...	...	...	...	100.0	...	...
5	SW	48.6	18.2	100.0	...	33.3	100.0	100.0	...	62.5	...	...
6	ML	57.1	94.4	...	...	28.6	...	100.0	...	100.0	...	...
7	ML	22.2	15.4	...	...	...	...	...	100.0	100.0	100.0	...
8	VPA	...	100.0	...	...	...	...	...	...	...	...	...
9	VPA	...	66.7	...	...	...	...	...	...	...	...	...
10 = 0	SL	100.0	100.0	100.0	50.0	...	50.0	...	...	50.0	100.0	...
11 = A	MW	33.3	65.0	100.0	...	50.0	...	100.0	50.0	33.3	100.0	...
12 = B	MW	13.3	46.7	...	100.0	100.0	100.0	100.0	87.5	33.3	100.0	...
13 = C	ML	77.3	47.1	...	100.0	...	83.3	75.0	100.0	...	...	...

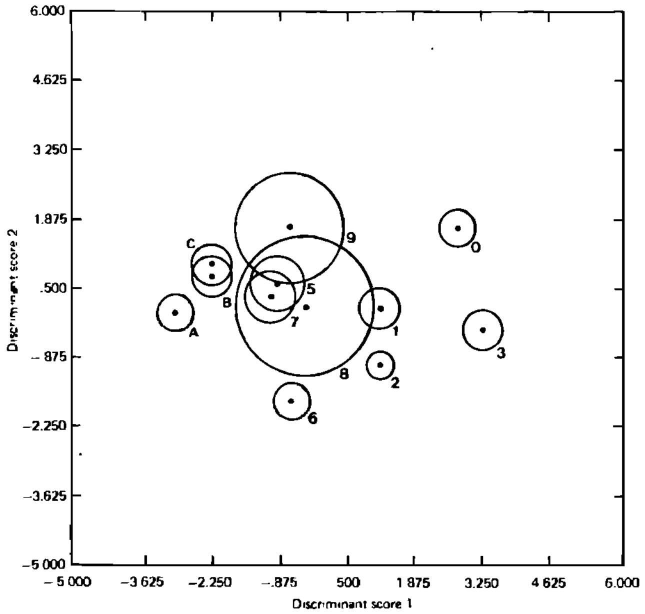

FIG. 15. Discrimination among individuals using a downscream.

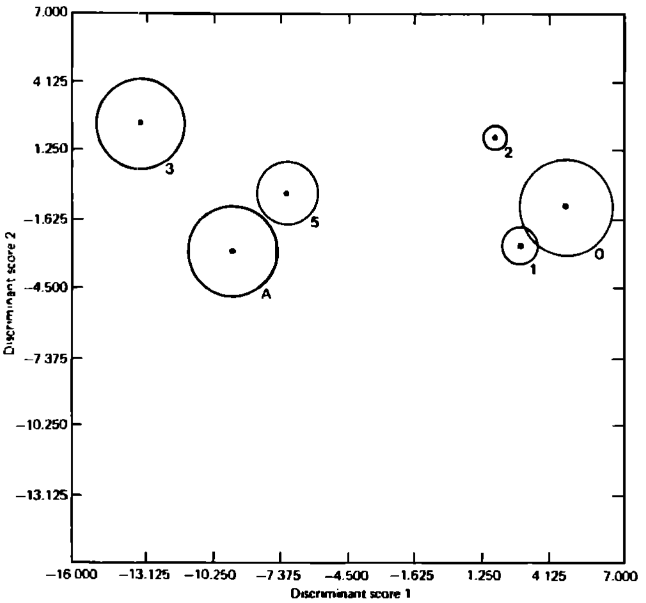

FIG. 16. Discrimination among individuals using a creak.

TABLE III. Discrimination among oceanariums by sound type.

Sound type	Percent of cases correctly classified	Number of groups (= oceanariums) represented
Upscream	62.1	4
Downscream	73.1	5
Creak	47.4	3
Whine	89.7	4
Whistle	60.9	3
Tone	89.3	4
Buzz	91.4	3
Ricochet	92.7	2
Click burst	72.4	4
Chatter	85.7	4
Seesaw	Not enough groups	

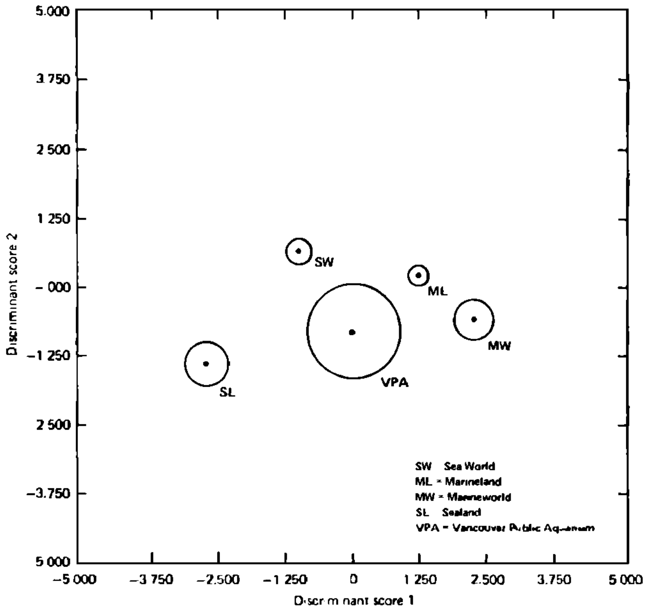

FIG. 17. Mean scores and 95% confidence circles on the first two discriminant axes for the individuals producing downscreams at each oceanarium.

information was detectable in the vocalizations produced by killer whales. Whether *O. orca* actually uses these differences is a reasonable but untested conjecture. Locating a food source, coordinating hunting activities, and maintaining group/social cohesiveness during group movement would appear to require a sophisticated mechanism that is likely to be acoustical. Although vision is well developed in killer whales, acoustics undoubtedly plays the most important role in the water where vision is limited.

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TABLE IV. Discrimination between sexes by sound type.

Sound type	Percent of cases correctly classified
Upscream	68.9
Downscream	65.1
Creak	100.0
Whine	96.6
Whistle	60.9
Tone	71.4
Buzz	91.4
Ricochet	85.4
Click burst	79.3
Chatter	100.0
Seesaw	90.9

sity of Washington's CDC computer. G. W. Priebe's (National Marine Mammal Laboratory) expertise contributed significantly to the computer analysis. Leola Hietala assisted in the final typing of this paper. W. A. Watkins, M. F. Tillman, and M. Novacek critically reviewed this manuscript.

[1]Use of trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

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