Time patterns of sperm whale codas recorded in the Mediterranean Sea 1985–1996

G. Pavan
Centro Interdisciplinare di Bioacustica e Ricerche Ambientali (CIBRA), Università degli Studi di Pavia, Via Taramelli 24, 27100 Pavia, Italy and Department of Urban Science, IUAV, Venice, Italy

T. J. Hayward
Naval Research Laboratory, Washington, DC 20375

J. F. Borsani,[a] M. Priano, M. Manghi, and C. Fossati
Centro Interdisciplinare di Bioacustica e Ricerche Ambientali (CIBRA), Università degli Studi di Pavia, Via Taramelli 24, 27100 Pavia, Italy

J. Gordon
Wildlife Conservation Research Unit, Department of Zoology, University of Oxford, South Parks Road, Oxford 0X1 3PS, United Kingdom

(Received 19 July 1999; accepted for publication 7 March 2000)

A distinctive vocalization of the sperm whale, *Physeter macrocephalus (=P. catodon)*, is the coda: a short click sequence with a distinctive stereotyped time pattern [Watkins and Schevill, J. Acoust. Soc. Am. **62**, 1485–1490 (1977)]. Coda repertoires have been found to vary both geographically and with group affiliation [Weilgart and Whitehead, Behav. Ecol. Sociobiol. **40**, 277–285 (1997)]. In this work, the click timings and repetition patterns of sperm whale codas recorded in the Mediterranean Sea are characterized statistically, and the context in which the codas occurred are also taken into consideration. A total of 138 codas were recorded in the central Mediterranean in the years 1985–1996 by several research groups using a number of different detection instruments, including stationary and towed hydrophones, sonobuoys and passive sonars. Nearly all (134) of the recorded codas share the same ''3+1'' (/// /) click pattern. Coda durations ranged from 456 to 1280 ms, with an average duration of 908 ms and a standard deviation of 176 ms. Most of the codas (a total of 117) belonged to 20 coda series. Each series was produced by an individual, in most cases by a mature male in a small group, and consisted of between 2 and 16 codas, emitted in one or more ''bursts'' of 1 to 13 codas spaced fairly regularly in time. The mean number of codas in a burst was 3.46, and the standard deviation was 2.65. The time interval ratios within a coda are parameterized by the coda duration and by the first two interclick intervals normalized by coda duration. These three parameters remained highly stable within each coda series, with coefficients of variation within the series averaging less than 5%. The interval ratios varied somewhat across the data sets, but were highly stable over 8 of the 11 data sets, which span 11 years and widely dispersed geographic locations. Somewhat different interval ratios were observed in the other three data sets; in one of these data sets, the variant codas were produced by a young whale. Two sets of presumed sperm whale codas recorded in 1996 had 5- and 6-click patterns; the observation of these new patterns suggests that sperm whale codas in the Mediterranean may have more variations than previously believed. [S0001-4966(00)02706-5]

PACS numbers: 43.80.Ka, 43.80.Gx [WA]

INTRODUCTION

The typical vocalization patterns of sperm whales, *Physeter macrocephalus (=P. catodon)*, engaged in long, deep feeding dives are extended sequences of loud clicks produced at regular rates of approximately 0.5–2 clicks per second. Feeding sperm whales rarely produce clicks at the surface, usually falling silent a few minutes before reaching the surface and resuming clicking some 30–90 s after fluking up to commence a dive (Gordon *et al.*, 1992; Mullins *et al.*, 1988). Such vocalizations were termed ''usual'' clicking by Watkins and Schevill (1977); we will also refer to these vocalizations as ''regular'' clicking. Occasionally, sperm whales also produce short click sequences with distinctive stereotyped time patterns. Watkins and Schevill (1977) first described hearing these patterned clicks during long regular click sequences, and because they usually came at the end of sequences, they named them ''codas.''

Typically, only a small number of codas are heard in such situations. For example, Mullins *et al.* (1988) heard no codas from two separate males recorded off Nova Scotia, while Gordon *et al.* (1992) heard codas on only 2 out of 40 days of nearly continuous monitoring of the vocalizations of feeding mature males of Kaikoura, New Zealand. Higher rates of coda production, including quite vigorous coda ex-

[a]Present address: Istituto Centrale per la Ricerca Applicata al Mare (ICRAM), via di Casalotti 300, 00166 Roma, Italy.

TABLE I. Year, data source, total duration of analyzed recordings, presence of codas, minimum number of animals present and storage medium analyzed for data sets in which sperm whale sounds were recorded. The storage medium refers to the medium in which recordings were made available for the present work. Recordings from the same source have been grouped even if they were made in different cruises or at different locations.

Year	Source	Duration	Codas observed?	Minimum number of whales recorded	Storage medium analyzed
1985	WHOI	cuts	yes	undetermined	data files
1988	Tethys	1 h 20 min	no	2	open reel
1989	Tethys	2 h 30 min	no	5	open reel
1990	Tethys	30 min	no	1	open reel
1991	CIBRA-Tethys	12 h 45 min	yes	4	DAT
1992	CIBRA-Tethys	7 h	yes	2	DAT
1993	CIBRA-Tethys	5 h	no	3	DAT
1994	CIBRA	16 h 20 min	yes	2	DAT
1994	IFAW	cuts	yes	undetermined	DAT
1995	CIBRA-Italian Navy	7 h 25 min	no	1	DAT
1995	Italian Navy	1 h	yes	7	DAT
1996	CIBRA	27 h	yes	10	DAT
1996	Saclant Center	3 h	yes	3	data files
1996	Italian Navy	1 h	no	4	DAT
1997	CIBRA	19 h 30 min	no	13	DAT

changes, are often heard from tight social groups of females and immature males interacting at the surface. Much of the more recent research on codas has been based mainly on analysis of recordings made in such situations (e.g., Moore *et al.*, 1993; Weilgart and Whitehead, 1993; Weilgart and Whitehead, 1997). Major studies of codas from the Galapagos and the Caribbean (Weilgart and Whitehead, 1993 and Moore *et al.*, 1993, respectively) have reported several distinctive codas varying from each other in both click number and pattern. The total number of distinctive codas reported from each area was remarkably similar: 23 from the Galapagos and 28 from the Caribbean.

Weilgart and Whitehead (1997) compared coda repertoires at several different levels: between social units encountered on different occasions within the same area; between ''places'' (areas of a few thousand kilometers across); between large geographical areas; and finally between oceans. They found strong group-specific dialects overlaid on weaker geographical variation. There were significant differences in repertoires between oceans (Watkins *et al.*, 1985; Weilgart and Whitehead, 1988; Weilgart, 1990; Moore *et al.*, 1993; Weilgart *et al.*, 1993; Borsani *et al.*, 1997; Pavan and Borsani, 1997; Weilgart and Whitehead, 1997; Whitehead *et al.*, 1998).

Within a broad research project on the acoustic behaviors of cetaceans in the Mediterranean Sea, more than 100 hours of recordings of sperm whale sounds, now archived in a Cetacean Sound Library (Priano *et al.*, 1997), were collected from multiple sources (see Table I) and analyzed. This ongoing research project is aimed at adding new data to our knowledge base concerning sperm whales and their acoustic behavior in the Mediterranean Sea in order to improve understanding of the population size, structure and trend in time and to support conservation efforts. Bioacoustic characteristics of particular interest in this research include the temporal patterns and waveform features of sperm whale vocalizations.

In this work, we characterize statistically the time patterns of clicks within sperm whale codas, and the repetition patterns of the codas themselves, in material recorded over a period of 12 years from widely dispersed locations in the Mediterranean Sea. A total of 138 codas, collected by six research groups, are analyzed to describe a coda pattern that may be typical of the Mediterranean. The results include interclick interval (ICI) measurements and their statistical distributions as well as coda repetition patterns. Interpulse interval (IPI) measurements are also performed on the component pulses of the clicks within the codas to estimate whale sizes and to aid in associating codas with individual whales.

Section I describes the instruments and methods of data collection by several research groups and catalogs the codas contained in the data sets. Section II describes the analysis of the coda data. Section III presents the results, including the context of coda observations and statistical characterizations of coda repetition patterns, series lengths, and temporal patterns of clicks. Section IV summarizes the results, interprets them in the context of previous research on sperm whale vocalizations and discusses their implications.

I. DATA COLLECTION

Underwater recordings of sperm whale sounds were made in the central Mediterranean Sea by six research groups in the years 1985–1997 using a number of different detection instruments, including stationary and towed hydrophones as well as sonobuoys and passive sonars (see Fig. 1 and Table I).

The earliest recordings we analyzed were made in 1985 near Malta by W.Watkins of the Woods Hole Oceanographic Institution (WHOI) and colleagues (W. Watkins, personal communication). They collected eight codas from an undetermined number of animals; these codas were made avail-

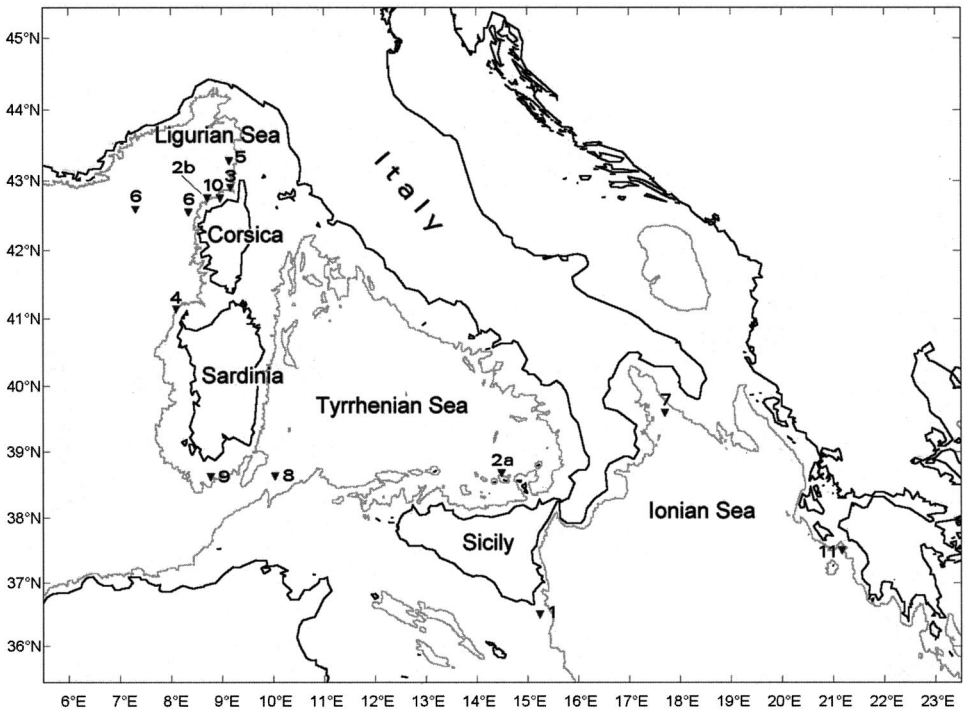

FIG. 1. Recording sites for 136 sperm whale codas (numbers according to Table II): (1) W. Watkins (WHOI), Malta 1985 (9 codas); (2a) CIBRA-Tethys, Aeolian Islands 1991 (9 codas); (2b) CIBRA-Tethys, Corsica 1991 (1 coda); (3) CIBRA-Tethys, Corsica 1992 (6 codas); (4) CIBRA, Sardinia 1994 (7 codas); (5) CIBRA, Corsica 1994 (7 codas); (6) J. Gordon (IFAW), Ligurian Sea 1994 (2 sites, 15 codas); (7) Italian Navy, Gulf of Taranto 1995 (2 codas); (8) Italian Navy-CIBRA, Sardinia 1995 (10 codas); (9) Italian Navy, Sardinia 1995 (8 codas); (10) CIBRA, Corsica 1996 (54 codas); and (11) Saclant Center, Greece (8 codas). The gray line is the 1000-m bathymetric contour.

able as data files belonging to the *SOUND* database of marine animal vocalizations developed at WHOI (Watkins *et al.*, 1992).

In July 1988 and August 1989, the Tethys Research Institute recorded sperm whale vocalizations each time animals were visually sighted; 1 h of recordings in 1988 and 3 h in 1989 were collected. Recordings were made using an ITC8073 preamplified hydrophone connected to an Uher 4400 Report Monitor tape recorder (tape speed 19 $\mathrm{cm\,s^{-1}}$).

In subsequent years (1991 to 1997), the research team of the Interdisciplinary Center for Bioacoustics and Environmental Research (CIBRA) of the University of Pavia, Italy, conducted auxiliary sailing vessel cruises in the Mediterranean Sea, gathering data on the distribution and the acoustic behavior of sperm whales and other cetacean species. The acoustic data were collected using wide-band towed arrays and digital audio tape (DAT) recorders.

Cruises in 1991, 1992 and 1993 were conducted within a joint research program between CIBRA and Tethys; cruises in 1994 were organized by CIBRA; cruises in 1995 were organized by CIBRA and the Italian Navy; cruises in 1996 and 1997 were organized by CIBRA and the association Ambiente Mare (Rome). In 1996, additional sperm whale codas were recorded by the NATO Saclant Center for Undersea Research (La Spezia, Italy).

As sperm whales are relatively difficult to find by visual search methods alone, acoustic techniques were used in the CIBRA cruises to detect, track and locate them. The procedure was to listen 24 h a day for at least 5 min every 30 min while towing an array of hydrophones at speeds of 7 to 10 $\mathrm{km\,h^{-1}}$.

The towed array used to collect most of the recordings (those made during the years 1994–1996) consists of an oil-filled, acoustically transparent hose 12 m long and 6 cm in diameter holding two groups of acoustic transducers spaced 8 m apart (Pavan and Borsani, 1997).

Upon detection, whales were acoustically tracked and approached by estimating their bearing through binaural audition of the hydrophone output signals and through computer-aided direction finding based on arrival-time differences of the clicks on the two transducer groups of the array. DAT recorders were started as soon as the signal-to-noise ratio was high enough to provide good-quality continuous recordings. In 600 h spent listening underwater, more than 100 h of recordings were made. A description of the instrumentation is provided by Pavan and Borsani (1997).

After the whales were approached, photographs of their flukes were taken whenever possible, resulting in the photo-identification of five individual whales on six occasions. One whale was sighted twice, in 1995 and 1996 (Pavan *et al.*, 1999).

In summer 1994, the research vessel SONG OF THE WHALE of the International Fund for Animal Welfare (IFAW) recorded 19 codas using similar equipment and procedures to those described above (Leaper *et al.*, 1992).

In 1995, several codas were recorded by the Italian Navy within a joint research project with the University of Pavia. Recordings were made with DIFAR (2.4-kHz bandwidth) and MISAR (10-kHz bandwidth) sonobuoys deployed by anti-submarine warfare (ASW) patrolling aircraft and by a submarine (Pavan, 1996; Pavan *et al.*, 1997a).

In 1996, the NATO Saclant Center for Undersea Research (La Spezia, Italy) recorded several sperm whales with the passive receiver of the LFAS (low frequency active sonar) system. Among the recordings, three sets of codas were found, two of them with variant click patterns (D'Amico, 1998).

TABLE II. Recordings in which sperm whale codas were found: Data set, research organization, location, month and year recorded, number of codas and number of coda series and coda bursts, number of whales emitting codas and whale IDs, estimated whale length, number of other whales detectable in the area, and acoustic receiver.

Data set	Source	Location	Date	Number of codas; series/bursts	Number of whales; ID/photo	Estimated whale length (m)	Number of other whales detectable	Receiver
1	WHOI	Malta	August 1985	9 n.d.	n.d. …	n.d.	n.d.	Stationary hydrophones
2a	CIBRA-Tethys	Aeolian Islands	July 1991	9 3/3	1 SW0791	13.5	1	towed array
2b	CIBRA-Tethys	Corsica	September 1991	1 1/1	1 …	n.d.	2	towed array
3	CIBRA-Tethys	Corsica	September 1992	6 2/2	1 …	12	0	towed array
4	CIBRA	Sardinia	June 1994	7 1/1	1 SW0694	12.7	1	towed array ALENIA
5	CIBRA	Corsica	September 1994	7 2/2	1 SW0994	12.0	1	towed array ALENIA
6	IFAW	Ligurian Sea	Summer 1994	15[a] 4/5	1 or 2	12.5 n.d.	n.d.	towed array
7	Italian Navy	Gulf of Taranto	May 1995	2 1/1	1 …	13.2	1	wideband sonobuoy
8	Italian Navy	Sardinia	October 1995	10 1/2	1 …	n.d.	2	DIFAR sonobuoy
9	Italian Navy	Sardinia	April 1995	8 1/1	1 …	n.d.	n.d.	submarine
10	CIBRA	Corsica	September 1996	54[b] 8/17	2 or more SW0996B SW0996C	9.3 12.3	>1	towed array ALENIA
11	Saclant Center	Greece	May 1996	8 n.d.	1 …	n.d.	>3	LFAS passive

[a]Two or three more codas were partially masked by noise; coda onset times were estimated for two of these.
[b]An additional series of two codas was not recorded.

II. DATA ANALYSIS

In all, more than 100 h of sperm whale recordings were analyzed to find codas and to determine, whenever possible, the context in which codas were produced. All of the data files and recordings were analyzed with the real-time Digital Signal Processing Workstation (DSPW) developed at CIBRA (Pavan, 1992, 1994; Pavan and Borsani, 1997). The browsing and analysis of this large amount of data were greatly facilitated by the real-time capabilities of the DSPW.

A total of 138 codas were identified; click timings were measured for 136 of them. Two codas in data set 6 were partially masked by incidental noise and therefore their click timings could not be measured; however, their coda onset times were estimated. Two other codas were heard in the 1996 cruise but were not recorded. Table II reports information on the recordings in which codas were found. Codas occurred in a wide geographic area (see Fig. 1).

For each coda, a spectrogram was computed and displayed. The time intervals between the first click and each subsequent click were measured on-screen with an accuracy of ± 2 ms by placing a cursor on the onset of each click [see Fig. 2(a)]. We also measured the intervals between consecutive codas emitted by the same whale by measuring the interval between the onset of the first click of each coda and the onset of the first click of the next coda.

Each click emitted by a sperm whale consists of multiple pulses, hypothetically associated with multiple internal reflections of the initial pulse within the spermaceti organ in the whale's head (Norris and Harvey, 1972; Clarke, 1978; Gordon, 1991; Goold, 1996) (see Fig. 3). The interpulse interval (IPI) is defined as the interval between the first and second pulses. Whenever possible, measurements of the IPIs of the clicks in the codas, and the IPIs of regular (noncoda) clicks preceding the codas, were made to aid in discriminating codas from different whales and to provide estimates of the length of the emitting animal (Clarke, 1978; Gordon, 1991; Goold, 1996; Pavan *et al.*, 1997b; Pavan *et al.*, 1999). The IPI measurements were based on cepstrum analysis of the time series and were made using the cepstrogram (cepstrum vs time) display available on the DSPW along with the spectrogram (spectrum vs time) display [see Fig. 2(b)]. The animal length estimates were then computed based on the empirical formula

$$L = 4.833 + 1.453\mathrm{IPI} - 0.001\mathrm{IPI}^2$$

from Gordon (1991) (see Table II). Although the correspondence between IPI and animal length has not been fully investigated, the IPI data provided information for discriminating clicks emitted by different animals when more than one animal was present.

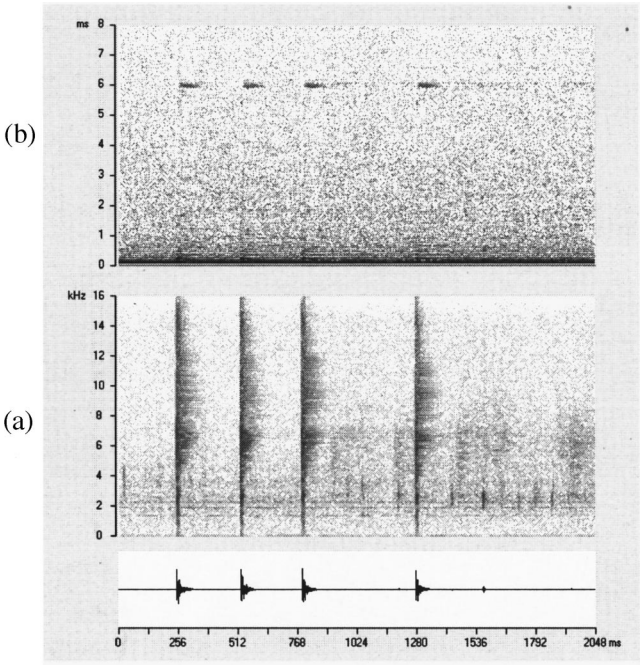

FIG. 2. (a) Spectrogram of a ''3+1'' (/// /) coda. (b) Corresponding cepstrogram showing interpulse interval of approximately 6 ms (see Sec. III).

III. RESULTS

A. Context of coda occurrences

Sperm whale acoustic contacts and sightings occurred at locations where the sea bottom depth ranged from 100 to 2600 m, though most of the sightings occurred where the bottom depth exceeded 1200 m. Codas were recorded at 12 sites over a wide area of the central Mediterranean (see Fig. 1).

Codas were heard and recorded only when two or more whales were acoustically detectable in the area in a period extending from 30 min before to 30 min after the codas occurred (see Table II). No codas were observed while recording isolated animals, i.e., while no other animals were detectable. During the CIBRA cruises, most of the codas observed were emitted by a whale at the end of its regular clicking bouts and just before it surfaced.

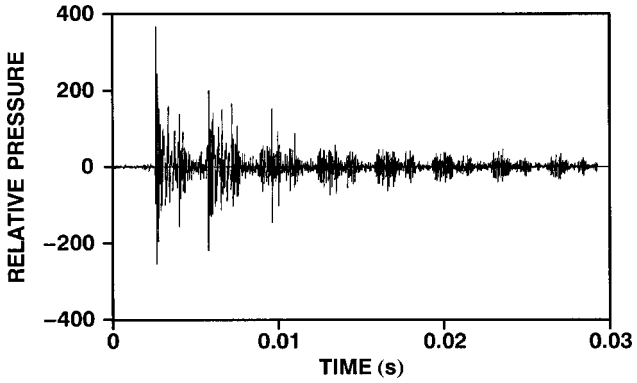

FIG. 3. Expanded time series plot of a single click from a sperm whale coda, showing the multiplepulse structure.

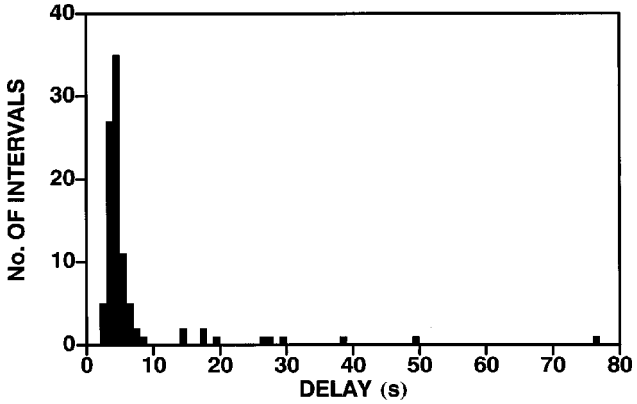

FIG. 4. Histogram of coda repetition intervals (CRIs) within the 20 series of two or more codas.

B. Coda repetition patterns and series lengths; coda bursts

Of the 138 codas, 17 were provided as individual data files; thus, no information about their patterns of production was available. Of the remaining 121 codas, 117 belonged to 20 series of 2 or more codas and 4 were isolated codas. In our statistical analyses, the isolated codas were treated as ''series'' of length 1. Each series consisted of up to 16 codas that were produced by the same whale. Within each series of length 2 or more, the coda repetition intervals (CRIs) were measured; for two consecutive codas, the CRI is defined as the interval between the onset of the first click of one coda and the onset of the first click of the next coda. In the 20 series of two or more codas, the 97 measured CRIs ranged from 2.76 to 77 s (mean 7.37 s, standard deviation 10.28 s). Figure 4 shows a histogram of the coda repetition intervals that occur within all of the coda series.

Within each of the 24 series, the codas occur in one or more ''bursts'' of fairly regularly spaced codas, separated by quiet intervals (see Fig. 5). A few of the bursts contain gaps

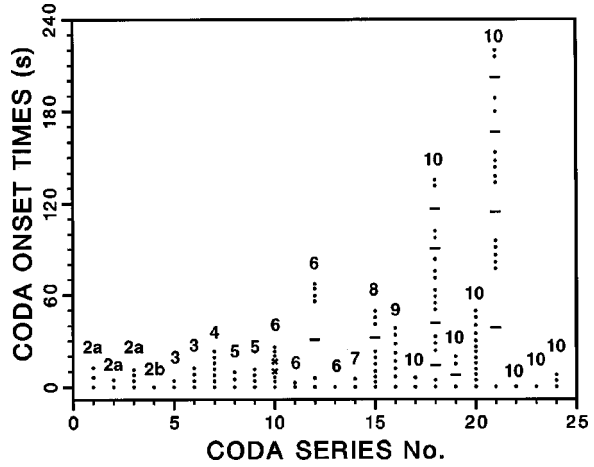

FIG. 5. Relative onset times (plotted as points) of the codas in each of 24 coda series (20 series of two or more codas and four isolated codas). In each series, codas occur in one or more ''bursts'' of fairly regularly spaced codas, separated by quiet intervals. The partition of the coda series into coda bursts is indicated by horizontal lines. The number above each series plot is the data set number from Table II. Estimated onset times of the two codas in data set 6 for which click intervals could not be measured are indicated by an ''×.''

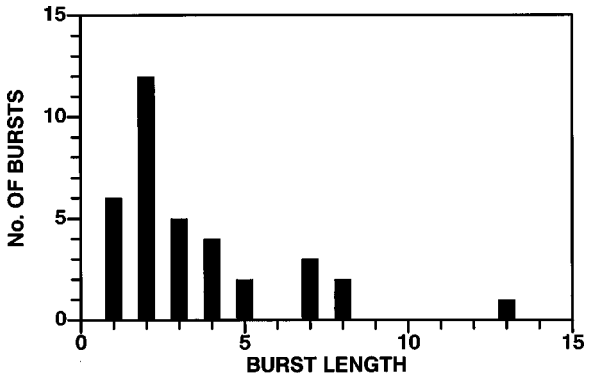

FIG. 6. Histogram of coda burst lengths (number of codas in each coda burst), taking 10 s as the threshold to separate bursts.

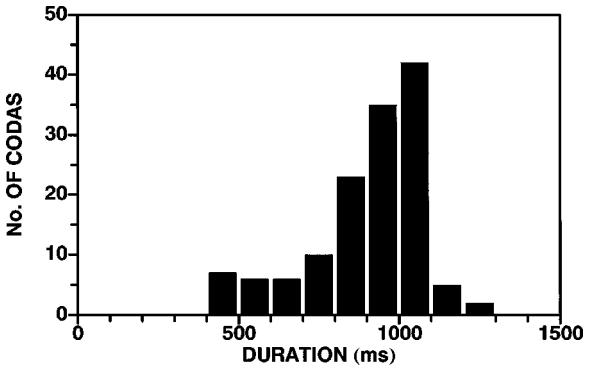

FIG. 8. Histogram of durations of 136 ''3+1'' codas.

that suggest the omission of a coda followed by resumption of regularly spaced codas.

If we take 10 s of silence as the threshold to separate coda bursts, then there were 35 coda bursts, with between 1 and 13 codas in a burst. The partition of the coda series into coda bursts is indicated by horizontal lines in Fig. 5. The mean number of codas in a burst was 3.46, and the standard deviation was 2.65. Figure 6 shows a histogram of the number of codas in each coda burst.

Of the 35 coda bursts, 17 consisted of 3 or more codas, hence two or more coda repetition intervals. The average of the coefficients of variation of the CRIs within each of these 17 coda bursts was 0.114.

C. Coda click patterns

Of the 136 codas that were measured, 134 match a ''3+1'' (/// /) click pattern. Two exceptional codas with embedded ''3+1'' patterns were found. In 1994, a coda in a series of seven had the 5-click pattern ''4+1'' (//// /). In 1995, a coda in a series of eight had the pattern ''3+2'' /// //. For each of these codas, the embedded pattern ''3+1'' was analyzed and included in the statistics.

Timings of the second, third, and fourth clicks (relative to the first click) were measured for each of the codas (see Fig. 7). The coda duration, defined as the time interval between the onsets of the first and last clicks, varied from 456 to 1280 ms. The mean duration was 908 ms, the standard deviation was 176 ms, and the coefficient of variation was 0.194. Figure 8 shows a histogram of the coda durations.

In a preliminary report (Pavan *et al.*, 1997a) based on a smaller sample (52 codas), it was shown that codas could be clearly divided into two different groups, ''short codas'' recorded in 1995, and ''normal codas'' recorded in previous years. With the increased data now available, the coda lengths have a statistical distribution that includes the intermediate values (see Figs. 7 and 8).

In some of the data files provided by the Saclant Center, short series of clicks, identified as probable sperm whale clicks, were found. The click patterns were ''1+2+2'' (see Fig. 9) and ''1+2+3'' (see Fig. 10). In the recordings, many animals appeared to be present and vocalizing at the same time at different bearings. This might be the first recording of a new coda pattern in the Mediterranean.

D. Rhythmic patterns of the codas

The results in Sec. III C show a wide variation in the durations of the ''3+1'' codas (see Figs. 7 and 8). However, since the rhythmic patterns (interval ratios) of all the codas appear similar when perceived aurally, we analyzed these patterns by considering the interclick intervals (ICIs) normalized by coda duration.

The click intervals within a 4-click coda may be described by three parameters: the coda duration D and the normalized intervals τ_1 and τ_2, which are the first and sec-

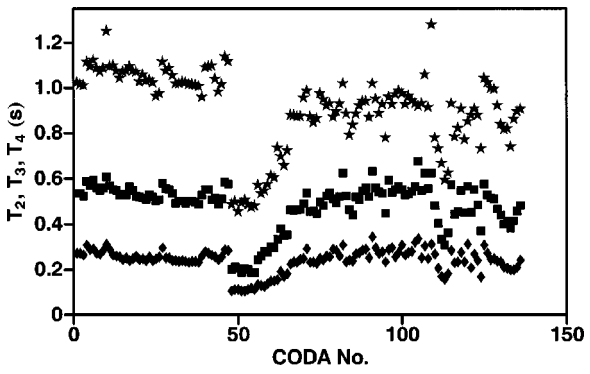

FIG. 7. Onset times (relative to first click onset) of the second (♦), third (■), and fourth (⋆) clicks in 136 ''3+1'' codas.

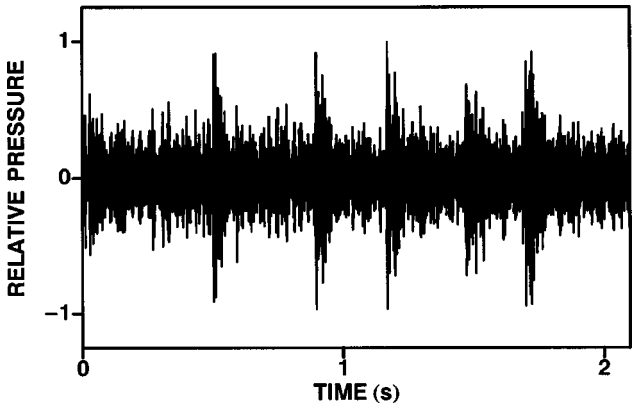

FIG. 9. Time series of a ''1+2+2'' click sequence.

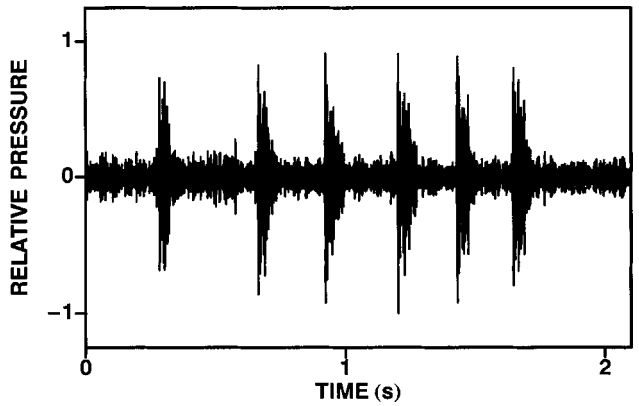

FIG. 10. Time series of a ''1+2+3'' click sequence.

ond interclick intervals divided by D. The parameters τ_1 and τ_2 completely determine the rhythmic pattern (interval ratios) of a coda, since the third normalized interclick interval is equal to $1\text{-}\tau_1\text{-}\tau_2$. Figure 11 shows a scatter plot of the pairs (τ_1, τ_2) for all 136 measured codas in data sets 1-11 and reveals a substantial variability in the coda rhythms.

Despite their overall variability, the coda rhythms are quite stable for data sets 1–8, which span a large variety of geographic locations and recording times (see Fig. 1 and Table II). Figure 12 shows a scatter plot of τ_1, τ_2 for all codas in data sets 1–8 and displays the high degree of stability of the normalized intervals for these data sets. For these data sets, the mean values of τ_1, τ_2, and $1\text{-}\tau_1\text{-}\tau_2$ were 0.248, 0.258 and 0.494, respectively; the ratios of these intervals are very close to the idealized 1:1:2 rhythmic pattern that is perceived aurally in the ''3+1'' coda. The coefficients of variation of τ_1 and τ_2 were 0.066 and 0.058, respectively, confirming the stability of the rhythmic pattern over these data sets.

Table III shows the means, standard deviations, and coefficients of variation of the three coda parameters τ_1, τ_2, and D for data sets 1–8 combined and for data sets 9, 10, and 11. The mean values of τ_1 and τ_2 for data set 10 differ from those for data sets 1–8 by 2.6 and 1.5 times the standard deviations of τ_1 and τ_2 for data sets 1–8, respectively. This

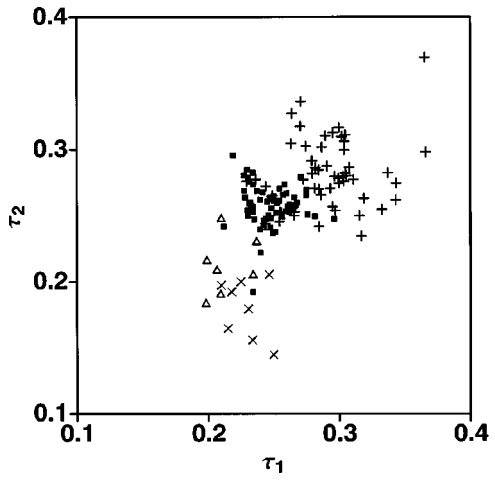

FIG. 11. Scatter plot of first and second normalized intervals (τ_1, τ_2) for 136 ''3+1'' codas: Data sets 1–8 (■), data set 9 (×), data set 10 (+) and data set 11 (△).

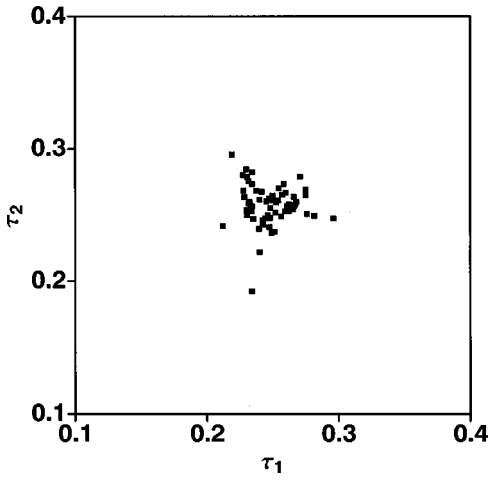

FIG. 12. Scatter plot of first and second normalized intervals (τ_1, τ_2) for the codas in data sets 1–8.

indicates a substantial deviation of the coda rhythms in data set 10 from those of data sets 1–8 (see also Fig. 11).

Most of the codas in data set 10 were produced by a relatively small whale whose length was estimated at 9.3 m, based on visual estimates and confirmed by a measured IPI of 3.07 ms (Pavan *et al.*, 1997c). According to Berzin (1971), this whale might be a 5-year-old male or a 7-year-old female. We also note that the codas produced by this whale were interspersed with single clicks and with pairs of clicks having the same interval as the first two clicks of the codas; the latter may have been incomplete codas or possibly 2-click codas.

The codas in data set 9 were unusually short and had highly variable durations. In addition, the signal-to-noise ratio for this data set was relatively low, and the click waveforms were noticeably distorted; this probably resulted from a long propagation path. These factors may have contributed, through measurement errors, to the untypical values of the normalized intervals for data set 9. The rhythmic patterns of the codas in data set 11 were intermediate between those of data sets 1–8 and those of data set 9 (see Fig. 11).

Table IV shows the correlation coefficients among the three coda parameters τ_1, τ_2 and D for data sets 1–8 and for data set 10. (The sample sizes were too small to report correlation coefficients for data sets 9 and 11.) Within each of these two data sets, the normalized intervals τ_1 and τ_2 had low correlations with each other and with the coda duration D, consistent with random variations in the production of a stereotyped interval ratio pattern. In data sets 1–8, the varia-

TABLE III. Means (μ), standard deviations (σ), and coefficients of variation (σ/μ) of the three coda parameters τ_1, τ_2, and D for data sets 1–8 (N=66) and for data sets 9 (N=8), 10 (N=54), and 11 (N=8).

Data set(s)	τ_1			τ_2			D		
	μ	σ	σ/μ	μ	σ	σ/μ	μ	σ	σ/μ
1–8	0.248	0.016	0.066	0.258	0.015	0.058	0.970	0.166	0.171
9	0.229	0.014	0.063	0.180	0.023	0.130	0.486	0.016	0.032
10	0.291	0.030	0.100	0.281	0.026	0.094	0.903	0.112	0.125
11	0.217	0.018	0.082	0.215	0.023	0.110	0.851	0.060	0.070

TABLE IV. Number of samples (N) and correlation coefficients among the three coda parameters τ_1, τ_2, and D for data sets 1–8, and data set 10. Correlation coefficients are not estimated for data sets 9 and 11 because of the small sample sizes.

Data set(s)	N	$\rho(\tau_1,\tau_2)$	$\rho(\tau_1,D)$	$\rho(\tau_2,D)$
1–8	66	−0.07	−0.02	0.25
9	8	⋯	⋯	⋯
10	54	0.21	−0.05	0.05
11	8	⋯	⋯	⋯

tions are those among 66 codas produced by nine or more individuals over a span of 11 years. In data set 10, the variations are those among 54 codas recorded on a single occasion; most of these were produced by one individual.

The coda parameters τ_1, τ_2, and D were generally stable within each coda series. The averages (over series) of the coefficients of variation of τ_1, τ_2, and D within each of the 20 series were 0.044, 0.047, and 0.039, respectively.

IV. SUMMARY AND DISCUSSION

A total of 138 sperm whale codas, recorded in the central Mediterranean Sea in the years 1985–1996, were analyzed to characterize statistically their series lengths, repetition patterns, and click interval patterns. Codas were heard and recorded only when two or more whales were acoustically detectable in the area, consistent with the hypothesis of a social function of sperm whale codas, as suggested by Watkins and Schevill (1977). Out of 121 codas found in continuous recordings, 117 belonged to coda series, each consisting of up to 16 codas. Each series consisted of one or more ''bursts'' of between 1 and 13 codas spaced fairly regularly in time.

Nearly all of the recorded codas had the same ''3+1'' (/// /) time pattern. Although the coda duration varied, the ratios of the interclick intervals remained highly stable for 8 of the 11 data sets and corresponded closely to the 1:1:2 interval ratio pattern perceived aurally. This suggests that it is information in the pattern of clicks within the coda rather than the coda duration which is conserved in temporally and spatially distributed encounters. Normalized interclick intervals had low correlations with each other and with coda duration. Codas with interval ratios substantially different from the nominal 1:1:2 pattern, recorded in 1996, were associated with a young whale. A small number of codas with very short durations and variant interval ratios were recorded in 1995.

The small size of the coda repertoire reported here and the extent to which it is dominated by a single distinctive pattern (''3+1'') is notable. Even some of the few ''aberrant'' codas had a ''3+1'' pattern embedded within them and might be considered to be occasional variations of the standard pattern. This contrasts with the extensive repertoires reported from other areas. Although ''3+1'' codas were reported from the Pacific, they were not particularly common there, accounting for only 1.5% of the codas analyzed by Weilgart and Whitehead (1997); neither are they among the more frequently heard codas in the Azores (Gordon, unpublished data).

Moore *et al.* (1993) suggested that codas might allow the identification of an assemblage of whales sharing, at least temporarily, the same area, while Weilgart and Whitehead (1997) proposed that codas were learnt within matrilineal social groups, so that group dialects reflected familial relationships. They also found that repertoires varied regionally.

A number of factors might contribute to the predominance of a single coda in observations made over a long period of time within the Mediterranean:

(a) The codas reported here were produced in the context of, and usually at the end of, sequences of ''usual'' clicks made during long feeding dives. Recordings analyzed by other teams have mostly been made from large socializing groups, often including apparent coda exchanges. Although similar in structure, codas produced in these two different situations may serve different functions, associated with different sized repertoires. Larger coda repertoires consisting of various 3-, 4-, 5- and 7-click codas have been observed recently in nursery groups in the Tyrrhenian and Ionian seas (Drouot and Gannier, 1999).

(b) Most of the codas analyzed here were produced by mature males; the smaller animal represented in data set 10 may have been an immature male. Males may have smaller repertoires than females, possibly reflecting the fact that once they leave their maternal groups they are less social. It is perhaps informative that on one occasion when variant codas were recorded (data set 11) a large number of whales were reported on different bearings, indicating the possible presence of a mixed group of females and immature males.

(c) The sperm whale population in the Mediterranean may be small and at least partially segregated from Atlantic populations.

Very little is known about the constituents of the sperm whale stock in the Mediterranean Sea (Notarbartolo *et al.*, 1993), the migration patterns within the basin and the extent of any movements across the Strait of Gibraltar, although data from several sources show that sperm whales regularly appear in the southern Tyrrhenian and Ligurian Seas in late spring, summer and early autumn. To understand more, acoustic techniques could be applied to study sperm whales more extensively in the Mediterranean Sea and to investigate their exchange with the Atlantic Ocean population as well as their movements in the eastern Mediterranean basin. Population-genetic analyses similar to those reported by Whitehead *et al.* (1998), along with analysis of coda repertoires throughout the Mediterranean and in adjacent Atlantic waters, might provide further evidence of a possible partial segregation of the Mediterranean population.

ACKNOWLEDGMENTS

This work was supported by the University of Pavia, the Italian Ministry of the Environment (Inspectorate for Sea Protection) and by the Italian Navy. The work of the second

author was supported by funds from the Office of Naval Research. We thank W. A. Watkins and the Woods Hole Oceanographic Institution for providing the recordings made in 1985; Tethys Research Institute for the cruises in 1991, 1992 and 1993; the International Fund for Animal Welfare for the recordings in 1994; the Italian Navy for the recordings in 1995; the NATO Saclant Center (La Spezia, Italy) for the recordings in 1996; the association Ambiente Mare for the cruises in 1996 and 1997; Giuseppe Notarbartolo di Sciara for his help in the earlier stages of the research; and Valeria Teloni for her work on the recordings made in 1996. Special thanks are due Alenia Elsag Sistemi Navali for the design and construction of the exellent array used in the cruises from 1994 to 1997.

Berzin, A. A. (**1971**). ''The sperm whale,'' Israel program for scientific translations, Jerusalem, p. 394, translated from Russian.

Borsani, J. F., Pavan, G., Gordon, J. C. A., and Notarbartolo di Sciara, G. (**1997**). ''Regional vocalizations of the Sperm Whale: Mediterranean codas,'' Eur. Res. Cetaceans, Cambridge (UK) **10**, 78–81.

Clarke, M. R. (**1978**). ''Structure and proportions of the spermaceti organ in the sperm whale,'' J. Mar. Biol. Assoc. U.K. **58**, 1–17.

D'Amico, A. (ed.) (**1998**). ''Summary Record and Report, SACLANTCEN Bioacoustics Panel, La Spezia, Italy, 15–17 June 1998,'' SACLANTCEN M133, Saclant Centre for Undersea Research, La Spezia, Italy.

Drouot, V. and Gannier, A. (**1999**). ''New sperm whale vocalizations recorded in the Mediterranean Sea,'' Eur. Res. Cetaceans, Cambridge (UK) **13**, 30–32.

Goold, J. C. (**1996**). ''Signal processing techniques for acoustic measurement of sperm whale body lengths,'' J. Acoust. Soc. Am. **100**, 3431–3441.

Gordon, J. C. D. (**1991**). ''Evaluation of a method for determining the length of sperm whales *Physeter catodon* from their vocalizations,'' J. Zool., London **224**, 310–314.

Gordon, J., Leaper, R., Hartley, F.G. and Chappell, O. (**1992**). ''Effects of whale-watching vessels on the surface and underwater acoustic behaviour of sperm whales off Kaikoura, New Zealand,'' Science and Research Series Publication, Department of Conservation, Wellington, New Zealand, Vol. 52, p. 64.

Leaper, R., Chappell, O., and Gordon, J. C. D. (**1992**). ''The development of practical techniques for surveying sperm whale populations acoustically,'' Rep. Int. Whal. Comm. **42**, 549–640.

Moore, K. E., Watkins, W. A., and Tyack, P. L. (**1993**). ''Pattern similarity in shared codas from sperm whales (*Physeter catodon*),'' Mar. Mammal Sci. **9**, 1–9.

Mullins, J., Whitehead, H., and Weilgart, L. (**1988**). ''Behaviour and vocalizations of two single sperm whales *Physeter macrocephalus*, off Nova Scotia,'' Can. J. Fish. Aquat. Sci. **45**, 1736–1743.

Norris, K. S., and Harvey, G. W. (**1972**). ''A theory for the function of the spermaceti organ of the sperm whale (*Physeter catodon*),'' in *Animal Orientation and Navigation*, edited by S. R. Galler, K. Schmidt-Koenig, G. J. Jacobs, and R. E. Belleville, NASA special publication SP-262, National Aeronautics and Space Administration, Washington, DC, pp. 397–417.

Notarbartolo-di-Sciara, G., Venturino, M. C., Zanardelli, M., Bearzi, G., Borsani, J. F., and Cavalloni, B. (**1993**). ''Cetaceans in the central Mediterranean Sea. Distribution and sighting frequencies,'' Boll. Zool. **60**, 131–138.

Pavan, G. (**1992**). ''A portable DSP workstation for real-time analysis of cetacean sounds in the field,'' Eur. Res. Cetaceans, Cambridge (UK) **6**, 165–169. The DSPW software is available on the web at ⟨www.unipv.it/cibra/instru.html⟩.

Pavan, G. (**1994**). ''A digital signal processing workstation for bioacoustical research,'' Atti 6 Conv. Ital. Ornit., Torino, 1991, 227–234.

Pavan, G. (**1996**). ''Cetacei nel Mediterraneo. Nuove strategie per lo studio dei mammiferi marini con la collaborazione della Marina Militare,'' Rivista Marittima, Roma, Anno CXXIX n. 5, 117–122.

Pavan, G., and Borsani, J. F. (**1997**). ''Bioacoustic research on cetaceans in the Mediterranean Sea,'' Mar. Fresh. Behav. Physiol. **30**, 99–123.

Pavan, G., Nascetti, D., Manghi, M., Priano, M., Fossati, C., and Borsani, J. F. (**1997a**). ''Bioacoustic research on Sperm Whales in cooperation with the Italian Navy,'' Eur. Res. Cetaceans **10**, 82–86.

Pavan, G., Priano, M., Manghi, M., and Fossati, C. (**1997b**). ''Software tools for real-time IPI measurements on sperm whale sounds,'' Proceedings Underwater Bio-Sonar and Bioacoustics Symposium. Proc. I.O.A. **19** (Pt. 9), Loughborough, UK, 157–164.

Pavan, G. Priano, M., Manghi, M., Fossati, C., and Bergamasco, C. (**1997c**). ''Sperm whales *Physeter macrocephalus* L. off the north-west coast of Corsica, France, in summer 1996, acoustic and surface behaviours,'' European Research on Cetaceans **11**, 218–221.

Pavan, G., Fossati, C., Manghi, M., and Priano, M. (**1999**). ''Acoustic measure of body growth in a photo-identified sperm whale,'' Eur. Res. Cetaceans, Cambridge (UK) **12**, 254–258.

Priano, M., Pavan, G., Manghi, M., and Fossati, C. **1997**). ''The cetacean sound library of the Interdisciplinary Centre for Bioacoustics and Environmental Research of the University of Pavia,'' *Proceedings Underwater Bio-Sonar and Bioacoustics Symposium*, Proc. I.O.A. **19** (Pt. 9), Loughborough, UK, 245–249. Samples of the recordings can be accessed on the web at ⟨www.unipv.it/cibra/sounds.html⟩.

Watkins, W. A., and Schevill, W. E. (**1977**). ''Sperm whale codas,'' J. Acoust. Soc. Am. **62**, 1485–1490 (with phonograph disk).

Watkins, W. A., Moore, K. W., and Tyack, P. (**1985**). ''Sperm whale acoustic behaviors in the southeast Caribbean,'' Cetology **49**, 15.

Watkins, W. A., Fristrup, K. M., Daher, M. A., and Howald, T. (**1992**). ''*SOUND* Database of Marine Animal Vocalizations; Structure and Operations,'' Technical Report WHOI-92-31, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts.

Weilgart, L. S., and Whitehead, H. (**1988**). ''Distinctive vocalizations from mature male sperm whales (*Physeter macrocephalus*),'' Can. J. Zool. **66**, 1931–1937.

Weilgart, L.S. (**1990**). ''Vocalizations of the sperm whale, *Physeter macrocephalus*, off the Galapagos Islands as related to behavioural and circumstantial variables,'' Ph.D. thesis, Dalhousie University Halifax, Nova Scotia.

Weilgart, L. S., and Whitehead, H. (**1993**). ''Coda communication by sperm whales (*Physeter macrocephalus*) off the Galapagos Islands,'' Can. J. Zool. **71**, 744–752.

Weilgart, L. S., and Whitehead, H. (**1997**). ''Group-specific dialects and geographical variation in coda repertoire in South Pacific sperm whale,'' Behav. Ecol. Sociobiol. **40**, 277–285.

Whitehead, H., Dillon, M., Dufault, S., and Weilgart, L. S. (**1998**). ''Non-geographically based population structure of South Pacific sperm whales: Dialects, fluke-markings and genetics,'' J. Anim. Ecol. **67**, 253–262.