Sperm whale codas

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Short series of 3 to 40 or more clicks are produced by sperm whales, *Physeter catodon*, in stereotyped repetitive sequences or codas. The temporal click patterns in codas appear to be unique to individual whales over at least a few hours. It is suggested that sperm whale codas serve as a means of individual acoustic identification. An apparent exchange of codas between two animals was analyzed and acoustical locations calculated from the four-hydrophone array data indicated that changes in underwater movement coincided with changes in the coda sequences.

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INTRODUCTION

An overlapping clatter of click series may usually be heard when listening underwater to sperm whales, *Physeter catodon* Linnaeus 1758. These characteristic trains of pulses were reported by Worthington and Schevill,[1] illustrated in published recordings by Schevill and Watkins,[2] and discussed more fully by Backus and Schevill.[3] In addition, multiple hydrophones were used by Watkins and Schevill[4,5] to derive from the sounds of sperm whales their underwater distribution, swimming behavior, and reactions in response to pinger sounds. Backus and Schevill[3] noted "sequences of clicks which are repeated several times," referring to the short series of clicks that we describe as codas in this report. Though they may be heard only occasionally, these click sequences stand out prominently against the background of the usual click sounds from sperm whales.

I. METHODS

Underwater recordings have been made whenever possible as we encountered sperm whales, so that since 1957 we have spent several hundred hours listening to these animals. Single hydrophones have been used as well as arrays of hydrophones in two and three dimensions. In this report, we refer to recordings made on a variety of equipment in past years, but the detailed analyses presented here were made with Celesco LC-34 hydrophones and a modified Pemco 110 tape recorder having a combined frequency response, within 3 dB from 20 Hz to 60 kHz. The sound analyses that are figured were made on a Kay Elemetrics 7029A spectrographic analyzer. Since this report is based on temporal patterns, no attempt was made to show the complete spectrum of clicks.

Array recordings were made and analyzed as described in detail by Watkins and Schevill.[4,6,7] In brief, the ship is stopped; hydrophones are put overboard (one off the stern, one off the bow, another is allowed to drift off to the side, and one is hung deep) to form an array with 30 m or more between units; sounds are introduced into the water for calibration of hydrophone positions and recording system response; the four channels of information are recorded on separate tape channels; signals are analyzed, compared, and cross correlated to derive sound arrival-time differences (measured to 0.1 msec); and three-dimensional locations are computed for relative hydrophone positions and then for the sperm whales' sounds.

A characteristic of analysis of sounds from such an array is that accuracy in computed direction of an underwater sound source is relatively reliable, but distance accuracy deteriorates rapidly beyond about ten times the array dimensions. This is a function of the error in the time difference measurements of the received signal.[6] However, these relative measurements produce highly repeatable relative locations. The computed locations in Fig. 6 were plotted relative to their direction from the array, with an accuracy of about one degree, and distance to the array was unspecified but estimated at more than 1 km. The animals were out of sight underwater during all of these acoustic events; their depths were not plotted in detail, but were generally the same throughout this period, as indicated by constant vertical angles of 10°–12°. We assumed equivalent errors in measurement for the sperm whale sounds of each sequence. For simplicity in our calculations, we also assumed constant sound velocity for each situation, as indicated by bathythermograms taken routinely with each use of the hydrophone array.

We use the musical term "coda" for the characteristic repetitive temporal pulse patterns that sometimes ended longer click sequences from sperm whales. These same stereotyped temporal patterns also were heard as discrete sound units (described below) and for consistency we have used the term for these also.

II. RESULTS

The click sounds of sperm whales sometimes were heard in repeated, stereotyped codas or short series of 3 to 40 or more clicks. The sequence or pattern of the clicks in a coda was usually about $\frac{1}{2}$ to $1\frac{1}{2}$ sec in duration and was repeated (2 to 60 or more times) almost exactly at variable intervals of a few seconds or minutes. The sound spectra of the clicks within a coda were similar, and successive codas had the same click repetition patterns and similar frequency emphases, probably indicating that they were produced by the same animal. The coda patterns appeared to be unique to individual sperm whales over the periods of observation.

A review of the situations in which we have recorded codas from sperm whales shows that they were heard in particular situations: (1) from whales that met underwater, when two separate groups came together, and when individuals approached each other, (2) as exchanges between whales that were not far apart, apparently reacting acoustically to each other; distant animals did not appear to exchange codas, (3) as sometimes eliciting silence in other more distant sperm whales, perhaps indicating attention (nearby whales quieted in response to short pinger sequences that were repetitive[4]), (4) as a response to unusual sounds, such as low frequency rumbling like that of an underwater landslide, the starting and stopping of ships' engines, or the passage of noisy aircraft (true also for 20-Hz sequences of *Balaenoptera physalus*[8]), and (5) only from submerged sperm whales.

Codas with a wide variety of click repetition patterns have been recorded. Relatively regular click repetition patterns are shown in Figs. 1 and 2. The nine-click coda (Fig. 1) was repeated 11 times in about 1 min. and the seven-click coda (Fig. 2) was repeated seven times in 31 sec. The more complicated rhythmic coda in Fig. 3 was repeated three times within $6\frac{1}{2}$ sec. The click patterns, general frequency emphases, and relative levels were all repeated with only minor variations at variable intervals of a few seconds to several minutes. Sometimes only one pattern was heard, and sometimes there were several different interspersed patterns, each coda maintaining its own identity of click sequence, frequency emphases, and relative level. Some of the variety of codas produced by sperm whales are illustrated in Table I. Note that perhaps the simplest variation was that of different repetition rates of the same number of clicks.

The replication of emphases and levels in repeated codas appears to confirm the aural impression that each pattern was produced by one whale. A coda with a particular click pattern seemed to be identified with one particular animal in a listening area. This was confirmed by computed directions and locations for sound sources from the hydrophone array (see below). Within at least a few minutes, each sperm whale within hearing range that produced a coda appeared to use one that was unique and at least temporarily separable from other whales' codas.

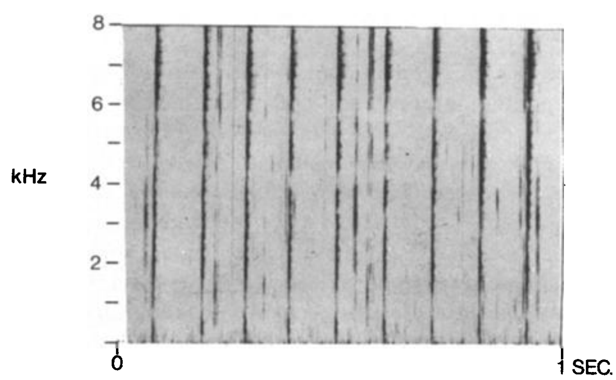

FIG. 1. This sound spectrogram of a nine-click coda from a sperm whale is the "nine-coda" from the exchange in Fig. 5. Clicks from other whales may be seen as background pulses at variable frequencies. A 300-Hz analyzing filter bandwidth was used.

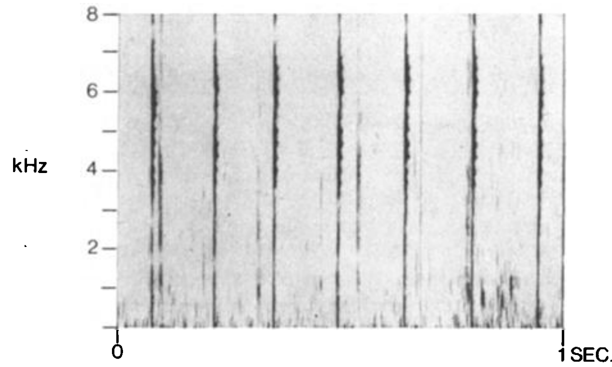

FIG. 2. The spectrogram of a seven-click coda from another whale is the "seven-coda" of the exchange in Fig. 5, and shows different frequency emphases. Analyzing filter was 300 Hz.

When codas were audible, more than one coda pattern could often be heard within 1 or 2 min, sometimes alternating and overlapping to demonstrate that more than one whale was involved. Codas were only heard while the whales were submerged so that the animals that produced the codas were never otherwise identifiable, and usually there were fewer coda patterns than there were whales. Though analysis of these sounds recorded on hydrophone arrays usually indicated different directions to whales producing different codas, they often were less than 10° apart, particularly when there appeared to be exchanges of codas. In contrast, analyses of the usual (noncoda) clicks from sperm whales generally indicated a relatively wide underwater distribution, with directional spreads of 100° or more.[5]

The greatest coda activity recorded was on 17 September 1962 at 40° 36'N, 65° 40'W. We saw 14 sperm whales. Within one 15-min recording, one coda pattern was repeated 66 times, another 34 times, etc. Table I gives a schematic representation of the most

TABLE I. The variety of click patterns in sperm whale codas is schematically represented, each mark representing a click. The codas are listed with the range of durations measured for each pattern and the number of repetitions of each coda that were identified in one 15-min recording made 17 September 1962 at 40°36'N, 65°40' W.

Coda Patterns	Duration (seconds)	No of times heard
/ // / ///	.98 – 1.02	66
// /////	.78 – .84	21
// / ///	.82 – .90	20
/ / / / /	1.03 – 1.05	3
/////	.77 – .85	34
/ / / / /	.90 – .98	25

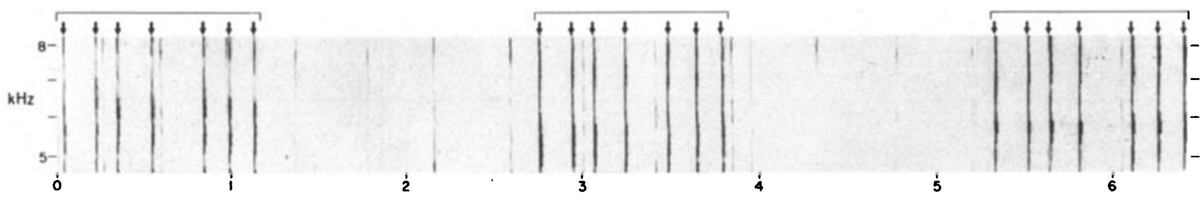

FIG. 3. A more complicated seven-click coda pattern is repeated three times. Only the 5–8-kHz range is included in this spectrogram in order to reduce confusion with other lower frequency background clicks. Analyzing filter was 150 Hz.

repeated patterns on this recording. Many more clicks from these and other whales filled the ambient noise and sometimes apparently obscured the codas.

Though the general arrangement of coda patterns did not change much over the listening periods, and individual patterns were distinguishable aurally, there were minor changes in temporal sequence from click to click within a coda, as well as variations in the duration of successive codas (Table I). One or more extra clicks were added sometimes to the end of some codas in a series, with no other variation to the rest of the coda pattern. The relative constancy of these patterns was demonstrable on at least two occasions in which we were sure that we had returned after about 1 h to the same area and apparently to the same animals, and we found the same coda patterns.

Relative levels of the clicks within each coda were usually much alike, but the first coda in a series was often 4–10 dB lower (about 4 dB in Fig. 3). As with other cetaceans[9] these whales appeared to change the level of their sounds at will.

The temporal coding that is characteristic of the stereotyped coda patterns was also occasionally noted in the regularity of the intervals between codas, so that the codas and the intervals appeared to become a part of a longer stereotyped sequence. In addition, temporal coding was evident at times in much longer click sequences from these whales. Such a complicated pattern is illustrated in Fig. 4, showing clicks (28 per sec) at the end of a longer 12-sec sequence. The last portion of this is very similar to an earlier segment of the same series. The ending coda comprising the last 11 clicks was repeated as a separate short coda heard along with three other codas during this recording in which two pairs of sperm whales were followed over about 4 h, (12 September 1975, $42^\circ 38'$N, $61^\circ 51'$W).

III. EXCHANGE OF CODAS

Thus it was apparent that each coda was produced by one sperm whale, that successive codas with temporal click patterns that were alike were produced by the same whale, and that interspersed codas were from two or more whales. Could these sequences be a purposeful exchange of codas?

A recording that included a possible exchange of nine-click and seven-click codas was chosen for detailed analysis (samples of each are shown in Figs. 1 and 2), and the entire sequence is reproduced at half-speed on the accompanying record. First the codas in this exchange are verbally numbered (according to Fig. 5) to help identify the sequence, and then the exchange is repeated without comment. A 75-Hz high-pass filter (Allison 2-BRW) was used in making the record.

The recording of this coda exchange was made at $37^\circ 42'$N, $73^\circ 28'$W, on 7 August 1972; four to five whales had been seen about 20 min earlier. The two codas were about 1 sec in duration with regular repetitions of nine and seven clicks per sec, respectively. The whales were estimated at perhaps 1 km distant and were out of sight underwater at about 200-m depth. In Fig. 5, the exchange is schematically detailed: the nine-click coda was answered by the seven-click coda for five alternations. But during the fifth exchange, the nine-coda was superimposed on the seven-coda, and the seven-coda continued (at the seven-click-per-sec rate) for two more clicks, now also nine clicks. Then there follows a fast

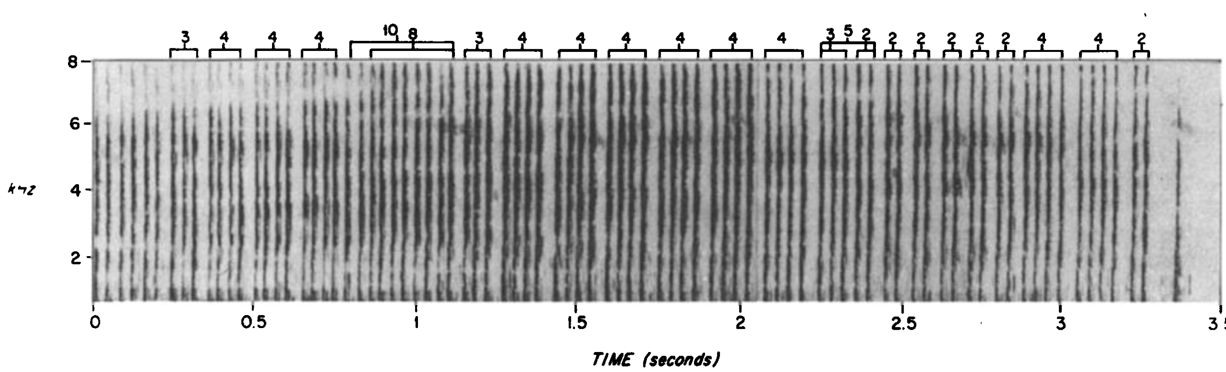

FIG. 4. The end of a 12-sec sequence of sperm whale clicks shows the same sort of temporal coding as found in the shorter coda patterns. A 300-Hz analyzing filter was used.

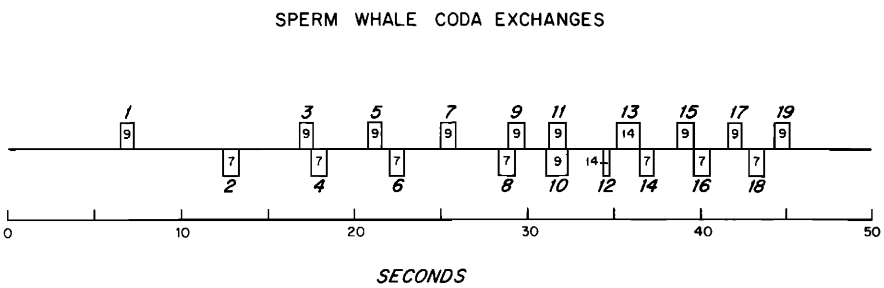

FIG. 5. An exchange of codas from two sperm whales is represented here. The nine-click codas of Fig. 1 from the first whale are shown as the odd-numbered codas above the line, and the even-numbered seven-click codas of Fig. 2 are from the second whale, shown below the line. The small numbers within the boxes indicate the number of clicks in each coda, and the larger italicized numbers denote the sequence of codas. Note the change that occurs at codas 10, 11, 12, and 13. The codas are drawn to fit their approximate duration and relative timing.

(about 35 per sec) series of 14 clicks apparently from the seven-coda whale, judging by relative frequency spectra. This fast 14-click series was answered by 14 clicks from the nine-coda whale at the nine-click-per-sec rate. And finally the whales returned to three more alternations of seven- and nine-click codas, respectively.

Since this was a four-hydrophone array recording, we attempted to extract all possible information relative to direction and acoustic location of the sources for this coda exchange. The plots in Fig. 6 show the results of this analysis, and computed locations for the coda clicks are separated into four groups along a horizontal reference line. Superimposing the four vertical lines (in Fig. 6) that slant toward the array would return the plots to their original relationship. The source locations are relative; there is no scale since we do not know the distance. The array had 30-m separations between hydrophones, and computed locations are plotted on a total field of about 40 by 60 m. The dimensions of the plots probably are not accurate since the whales were beyond the potential limits of precision for such a system,[6] however, relative progression of sequential locations and direction from the array probably are reliable. The numbers in Fig. 6 refer to the codas in Fig. 5, odd numbers for the whale with nine-click codas and even numbers for the whale with seven-click codas.

Individual clicks of each coda were analyzed and plotted (dots in Fig. 6) for all that could provide a location. The locations for each coda were enclosed to indicate the total scatter for each coda. The actual position for each whale at the time of the coda was likely to be the center of the enclosed scatter of points. There was a remarkable coherence in these computed locations, strengthening our belief that each coda was produced by one whale. The elongated scatter of points for

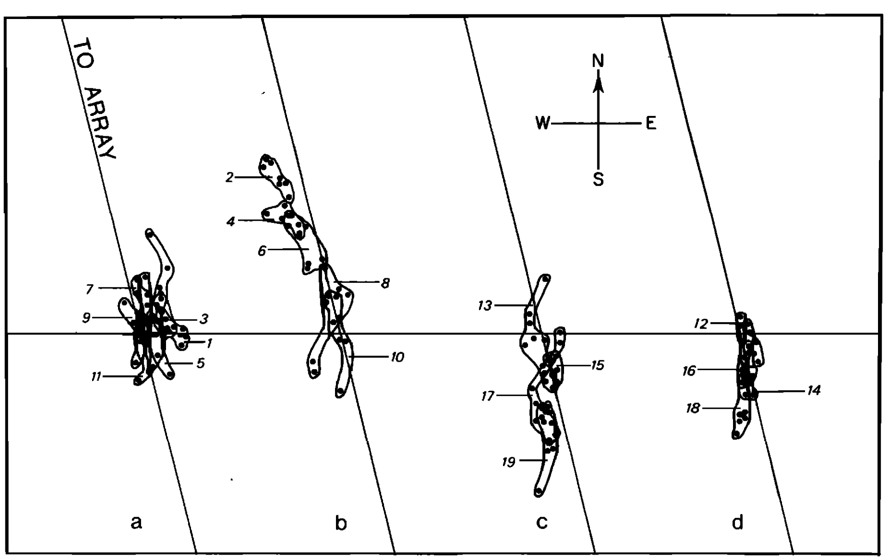

FIG. 6. Underwater movements of the two sperm whales that exchanged codas in Fig. 5 are indicated by plotting computed locations for the sounds of each whale. These are plotted on a total field of about 40 by 60 m, but the dimensions are arbitrary (see text). The plot is divided into four segments and separated along a horizontal reference line so that superimposing the four vertical lines that slant toward the array would return the plots to their original relationship. Each dot represents the location of a single click that was sufficiently above background to be computed. All the clicks for each coda are enclosed so that each enclosure represents the scatter of points for a particular coda. The codas are numbered according to those in Fig. 5: (a) the first odd-numbered codas from the nine-coda whale, 1, 3, 5, 7, 9, and 11; (b) the first even-numbered codas from the seven-coda whale, 2, 4, 6, 8, and 10; (c) the last of the odd-numbered codas from the nine-coda whale, 13, 15, 17, and 19; and (d) the last of the even-numbered codas from the seven-coda whale, 12, 14, 16, and 18. The nine-coda whale is first (a) stationary, then (c) moving S and W; the seven-coda whale (b) comes in from the N and W, then (d) moves S and W with the other whale.

each coda orientated generally toward the array, the result of small errors in measurements of sound arrival at the array hydrophones.[6,7]

The first six of the odd-numbered nine-click codas [1–11 in Fig. 6(a)] plot together in a group with very little obvious progression, except perhaps a little east-to-west shift in bearing from the array, considering the first to last of these codas. This represents 54 computed locations, from all the clicks in all six of these codas. The grouping would seem to indicate that this nine-coda whale was essentially stationary during this period, perhaps moving just a little to the west.

The second set of plots is of the first five even-numbered seven-codas [2–10 in Fig. 6(b)]. These plots represent 33 computed locations and a definite progression may be seen with successive codas. Though there is some overlap, the progression is away from the array and a little to the east.

The end codas of these two plots [Figs. 6(a) and (b)] are the two codas that occurred simultaneously, the nine-coda and the lengthened seven-coda (7+2) by both whales. If these two plots are superimposed (1–11 and 2–10) with the array lines shifted along the horizontal reference line to coincide, it will be seen that the even-numbered plot [Fig. 6(b)] ends near the center position for the odd-numbered plot [Fig. 6(a)]. Now the two whales appear to be together.

Beginning with the 14-click sequence of the nine-coda whale [13 in Fig. 6(c)] and plotting 34 locations for the clicks of the last four odd-numbered codas, we can now see a progression moving away from the array and a little to the west.

Similarly, beginning with the fast 14-click sequence of the seven-coda whale [12 in Fig. 6(d)], the last four even-numbered codas with 25 clicks plotted shows a continued progression away from the array and a change to a little east-to-west movement.

If these last two plots [13–19 and 12–18, Figs 6(c) and (d)] are superimposed, it will be seen that the nine-coda whale and the seven-coda whale are now moving together, both away from the array and to the west.

In these analyses, there was a coincidence of a change in the coda signals (simultaneous codas, change in pattern, temporarily lengthened sequence) at the time that the plots indicate that the two animals met, and then there was a change in progression: The nine-coda whale had been stationary but began to move away from the array and to the west, the seven-coda whale approached the other whale from the west and from the direction of the array, and on meeting the other whale, turned to move along with it in the east-to-west direction.

No more seven-codas were heard, but there were two more nine-codas about 20 sec later, and then after about 25 sec another two sequences of nine-codas were recorded. Computed locations for these codas indicated this whale had continued the same relative progression and direction of movement, away and to the west, and at the same rate.

IV. DISCUSSION

The analyzed coda exchange appears to have been an interaction between two whales. The interaction was confirmed, we think, by the coincidence of pattern modification with changes in underwater movement. Other probable coda exchanges were also studied and though many alternating sequences could be found, none were as clearly indicative of acoustic interactions.

The variations of computed location for successive coda clicks plotted in Fig. 6 reflect changes noted in relative sound arrival times on all the array hydrophones[6] (not just on one), which reduces the possibility that the progressions were only a result of time measurement errors. The differences noted for each whale show that the system was capable of discriminating between the sound sources. The coherence of position for successive clicks from the same whale makes us confident that the progressions were real, and that our interpretation of the acoustic interactions and the relative movements of the whales are correct.

Watkins and Schevill[5] noted from the usual direction of sound arrivals that sperm whales tended to return to the surface together, even though they were usually widely distributed underwater. If the coda serves an an individual identifier, it would be particularly useful when whales are separated. It is not surprising then to note that codas were not heard from whales while they were together at the surface. Codas were heard from animals that were widely separated underwater, but obvious exchanges seemed to occur only between whales that were relatively near each other. Exchanges of pulse bursts in the porpoise, *Stenella longirostris*,[9] also were heard from animals that were near each other.

The coda patterns identified individual sperm whales for us, at least over the 3–4 h we were able to maintain contact with some of the whales. Presumably codas also served as unique individual identifiers to other sperm whales as well. The frequency spectra signatures[3] of individual clicks could be modified by reverberation, reflections, and frequency selective absorption to the point of nonrecognition, perhaps making temporal coding generally a better identifier. Codas from different whales (different in level, frequency emphasis, direction) always were formed of sufficiently different temporal patterns so that they were immediately separable to our ears; the codas from different whales within acoustic contact were remarkably varied. This seems to suggest purposefully chosen identifications sufficiently varied from all other whales in an area over at least a particular time period.

Somewhat similar temporal coding of the underwater sounds of other marine animals also has been noted. Finback whales, *Balaenoptera physalus*, produce remarkably repeatable 20-Hz sounds at specific intervals over long periods, and like sperm whale codas they sometimes may be stimulated by unusual sounds.[8] Long (20 min or more), repeated, stereotyped song sequences have been described from humpback whales, *Megaptera novaeangliae*, but the same song appears to be sung by all the singing whales in an area.[10] Among pinnipeds, the bearded seal, *Erignathus barbatus*, produces long (2 min or more) repetitive song sequences,[11] and the walrus, *Odobenus rosmarus*, also uses repetitive pulse codas as a part of its acoustic displays.[12] In particular areas, repeated song sequences (usually longer series of sounds) were considered to be species specific, while codas were repeated (short) pulsed sequences often unique to individual animals.

Repeated sequences in the whistlelike calls of a variety of porpoises have been described and indicated as apparently unique to the individual: *Tursiops truncatus*,[13] *Lagenorhynchus obliquidens*,[14] and *Stenella plagiodon*.[15] Backus and Schevill[3] commented on the regularity and the similarity of repeated click sequences from sperm whales and suggested a unique click "signature" in individual clicks for each whale. Repetitive "salvos" were noted by Busnel and Dziedzic[16] to be different for different sperm whales and may have been a form of the codas we describe.

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[1] L. V. Worthington and W. E. Schevill, "Underwater sounds heard from sperm whales," Nature (London) 180, 191 (1957).
[2] W. E. Schevill and W. A. Watkins, *Whale and Porpoise Voices* (Woods Hole Oceanographic Institution, Woods Hole, MA, 1962), pp. 1–24 + phonograph record.
[3] R. H. Backus and W. E. Schevill, "*Physeter* clicks," in *Whales, Dolphins, and Porpoises*, edited by Kenneth S. Norris (University of California, Berkeley, 1966), pp. 510–528.
[4] W. A. Watkins and W. E. Schevill, "Sperm whales (*Physeter catodon*) react to pingers," Deep Sea Res. 22, 123–129 (1975).
[5] W. A. Watkins and W. E. Schevill, "Spatial distribution of sperm whales," Deep Sea Res. 24, 693–699 (1977).
[6] W. A. Watkins and W. E. Schevill, "Sound source location by arrival-times on a non-rigid three-dimensional hydrophone array," Deep Sea Res. 19, 691–706 (1972).
[7] W. A. Watkins, "Biological sound-source locations by computer analysis of underwater array data," Deep Sea Res. 23, 175–180 (1976).
[8] W. E. Schevill, W. A. Watkins, and R. H. Backus, "The 20 cycle signals and *Balaenoptera* (fin whales)," in *Marine Bio-Acoustics*, edited by W. N. Tavolga (Pergamon, Oxford, 1964), pp. 147–152.
[9] W. A. Watkins and W. E. Schevill, "Listening to Hawaiian spinner porpoises, *Stenella* cf. *longirostris*, with a three-dimensional hydrophone array," J. Mammal. 55, 319–328 (1974).
[10] R. Payne and S. McVay, "Songs of humpback whales," Science 173, 585–597 (1971).
[11] C. Ray, W. A. Watkins, and J. J. Burns, "The underwater song of *Erignathus* (bearded seal)," Zoologica 54, 79–83 (1969).
[12] G. C. Ray and W. A. Watkins, "Social function of underwater sounds in the walrus *Odobenus rosmarus*," Rapp. P.-V. Reun. Cons. Int. Explor. Mer, 524–525 (1975).
[13] M. C. Caldwell and D. K. Caldwell, "Individualized whistle contours in bottlenosed dolphins (*Tursiops truncatus*)," Nature 207, 434–435 (1965).
[14] M. C. Caldwell and D. K. Caldwell, "Statistical evidence for individual signature whistles in the Pacific whitesided dolphin (*Lagenorhynchus obliquidens*)," Cetology 3, 1–9 (1971).
[15] M. C. Caldwell, D. K. Caldwell, and J. F. Miller, "Statistical evidence for individual signature whistles in the spotted dolphin, *Stenella plagiodon*," Cetology 16, 1–21 (1973).
[16] R. -G. Busnel and A. Dziedzic, "Observations sur le comportement et les emissions acoustiques du cachalot lors de la chasse," Gocagiana 14, 1–15 (1967).