Investigations on cetacean sonar XI: Intrinsic comparison of the wave shapes of some members of the Phocoenidae family

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Abstract
A comparison of the acoustic waveforms of three different species, Phocoena phocoena, Phocoena sinus and Neophocaena phocaenoides of the subfamily Phocoeninae is made with the species Phocoenoides dallii of the subfamily Phocoenidae. The comparison is based on the successful mathematical modelling and identification of the clicks. As remarkable as it may seem, the polycyclic sonar signals of these species have the same basic wave shape in common, despite their somewhat longer time-duration frequency bandwidth product in relation to a Tursiops type click which lasts only a few cycles. In-depth analysis for the type of sonar click of the Phocoeninae subfamily reveals both a representation by a single pulse and a decomposition into a main pulse, followed within 16–20 μs after onset by an important reverberation. Both pulses can be modelled by the Gabor time function. For the P. dalli species we find a decomposition into three elementary pulses together giving rise to the unusual time duration of the click of 100 μs. The time difference between those first two pulses of the click—with identical dominant frequency—is conjectured to be an important parameter in the identification of the acoustic behaviour and is probably attributable to a morphological distinction inside the animal's head. This supports acoustically the subfamilial partition. Cluster analysis applied to the two highest ranking parameters of the click description, i.e. dominant frequency and either time duration or frequency bandwidth reveals a striking overlap in similarity in the click structure of the three members of the subfamily Phocoeninae and a distinguishable characteristic for the subfamily Phocoenidae. A cluster of clicks for Tursiops (open water) is added to this scatter plot as a reference to species with a different (higher) relative frequency bandwidth. As a linear, non-parametric measure of similarity in waveform, the cross-correlation factor for normalized frequency scale between P. sinus, P. phocoena and N. phocaenoides is calculated as 0.73 and 0.76.

Introduction
The purpose of this research was to establish whether there is a parametric fit of the sonar signals of the Vaquita (Phocoena sinus) into the sonar plot of other members of the family Phocoenidae. This parametric estimation is carried out by model forming based on the known time signal of Gabor. The modelling is justified again on the basis that we deal with time functions that have a rather short time duration-frequency bandwidth product, which is minimal for the Gabor signal. The first steps on the estimation of the Gabor model had already been done for N. phocaenoides sonar as an example of porpoise sonar (Kamminga et al., 1986). The results were promising, although there was a constraint in that we were dealing with a higher uncertainty product than for Tursiops sonar signals. The higher uncertainty product inspired us finally to a structure of decomposition into more than one elementary Gabor signal, which partly explains the comparatively long time duration of the actual porpoise click (Cohen Stuart, 1994). Following the first report on the acoustic signals recorded from Phocoena sinus—local name Cochino or Vaquita (Silver, 1991)—this paper treats a parametric description and subsequent comparison of the acoustic behaviour of three different Phocoenids, Phocoena phocoena, Neophocaena phocaenoides and Phocoenoides dallii with that of P. sinus. Attention is given to the individual sonar clicks as building blocks of the sonar click trains. Thus, it is possible to investigate the actual differences or similarities in the acoustic behaviour of four members of the two sub-families of the family Phocoenidae. To this end, high-quality, adequate bandwidth recordings in the wild as well as in captivity of these four species are used in the
here-presented cluster analysis and intrinsic parametric analysis of the waveforms. Given the hypothesis that membership of the same (sub-)family should be an indicator of similar acoustic behaviour, one might expect without doubt that a comparison based on a quantitative approach should reveal that Vaquita fits into the same cluster as *P. peruca* and *N. phocoenoides*. A comparison with the sounds of *P. dalli* should then be the most interesting, not only from an acoustical point of view, but also from the taxonomical side, as this species belongs to the other subfamily Phocoeninae of the Phocoenidae. This taxonomic point is separately treated below.

Phocoenidae vocalizations have been in the minority in the description of odontocete underwater sounds, especially as we take into account the frequency bandwidth of the recording gear needed for these high frequency echolocation signals. We note that the reports of *P. phocoena* by Duhrovskii, Kramm & Titov (1971), Mohl & Andersen (1973), Kanning & Worrall (1981), Kanning & Terly (1994). For *N. phocoenoides* we only have the observations by Evans et al. (1985) and a more detailed description by Kanning et al. (1986) about vocalizations recorded in a restricted environment (tank). For a third species, Silber (1991) presented the first description of sounds recorded from the phocoenid species *P. sinus*. Still missing altogether in this subfamily is the description of the acoustics of *P. spinipinnis* (Burnamter’s porpoise).

As far as we observe for the other subfamilies we only see adequate bandwidth recordings for *Phocoena*.*dallii*, recorded at sea by Awrey et al. (1979) and by Harcourt & Soo (1990) at sea as well as in a tank. Characteristic features of *Phocoena*.*dallii* are, in general, a small relative bandwidth of around 5 dominant frequency of the sonar clicks above 100 kHz with a number of cycles of more than six, and a typically low sound pressure level of an average of 160 db re 1 μPa at 1 m. (2001) refers to this class of signals as having a polyphonic waveform in contrast with the well-known Tursiops waveform with less than four cycles as a second category in the waveform classification (oligocyclic). At the time of writing, this category of the polyphonic waveforms is an incomplete minority with regard to the description of odontocete echolocation behaviour.

The outgoing clicks from the dolphin are submitted to a transmission beam pattern that has been shown to be directional to highly directional. Ati et al. (1980) measured Tursiops in the vertical and horizontal planes an average - 90 beamwidth of 10°. For the harbour porpoise only, we are left with a remark by Mohl & Andersen (1973) that the presence of high frequency was noted when the animal was pointing at the hydrophone with an angle of 30° C as was estimated from a photograph. Given the high dominant frequency, we are left with the supposition that the transmitting beam is more directional than for Tursiops.

**Taxonomy**

After finding the same physiological phenomenon in different species, one has to consider the origin of the similarity. It may be of a general nature and thus can be found in all the species of a large taxon (e.g., echolocation in Odontoceti), it could be linked with a particular anatomical structure found only in the studied species or it could be related to an adaptation to a particular ecological feature (e.g., a certain biotope). In this study, we accept the second possibility as the most logical one. *Phocoena phocoena*, *Phocoena sinus* and *Neophocaena phocaenoides* have skulls which remarkably resemble each other and also *Phocoena*.*dallii* skulls look very much like those of Harbour Porpoise (see Van Isele et al., 1977). The biotope of Dad’s Porpoise on the one hand and the biotope of the Harbour Porpoise, the Finless Porpoise and the Vaquita on the other hand are very different: the first one is a pelagic species, the other ones are coastal. If our conclusion that the phenomenon is linked with the anatomy of the skull and thus is a taxonomic feature, the *Phocoena spinipinnis* and *Stenella phocoena* should also show the same basic wave shape.

**Instruments, methods and subjects**

The acoustic signals of the *Phocoena sinus* were obtained by Silber (1989) in 1969 and 1987 at sea within 10-16 km off San Felipe, Baja California Norte. The geographical distribution of the Vaquita-porpoise appears to be restricted to a few areas in the Northern Gulf of California. Aerial sightings (Silber & Norris, 1991) indicate year-round seasonal distribution of this rarely encountered porpoise. Recordings were made with RESON hydrophone THC40/4 (frequency range up to 400 kHz) and backed up by a preamplifier and a Rascal Store 4DS tape recorder. A 500 Hz high-pass filter was used to protect against frequency distortions. System response at 30 ips recording speed thus resulted in flat frequency response (0 db) from 500 Hz to 150 kHz. Recordings were also made at a recording speed of 60 ips, thus extending the frequency range to 300 kHz. An example of a *P. sinus* click is shown in Figure 1. The *Phocoena phocoena* echolocation signals were obtained in 1989 from a young animal, stranded shortly after birth and expertly raised at the Point Defiance Zoo and Aquarium, Tacoma, Washington, it was six months old when taped.
Figure 1. Typical waveform of an echolocation click of *Phocoena sinus*. Signal-to-noise ratio is 31.8 dB. Recorded at sea in Baja California Norte.

Figure 2. (a) Typical waveform of a young *Phocoena phocoena* about six months old when recorded at the Point Defiance Zoo and Aquarium at Tacoma, Washington. Signal-to-noise ratio 31.7 dB. (b) An echolocation click of a rehabilitated by-catch *Phocoena phocoena*, recorded at the bioacoustics facility of the Odense University at Stril, Denmark. Signal-to-noise ratio 26.4 dB.

acoustically at that location, and from adult *Phocoena* at the acoustics facility of the Odense University at Stril, Denmark in 1993. The latter animals were rehabilitated victims of by-catch in Danish waters. Although our recordings in Odense revealed, besides the ever-present high frequency of around 125 kHz in the sonar clicks, also the 2 kHz and 20 kHz component, we opted for uniformity in comparison in choosing for the click trains without the low frequency components and then collected some 56 typical examples of clicks. Figure 2a shows an example of the Tacoma porpoise and Figure 2b pictures the adult Phoenoa. Furthermore, to exclude possible differences in hydrophone/amplifier combination, only the recordings made with the combination B&K hydrophone 8103 and the B&K charge amplifier 2635 were used in the final comparison with other *Phocoenidae* signals. The data obtained for the representation of the acoustic behaviour of *Neophocoena phocoenoides* (‘Yusho porpoise’) of the Japanese coastal popula-
tion was recorded in the Toba Aquarium, Toba City in Japan (Kamminga et al., 1990). These recordings were carried out with the same combination of hydrophone and amplifiers as the *P. phocoena* sounds. *N. phocaenoides* is a surprisingly quick and lively animal, emitting abundant click trains with stable pulse forms and with a pulse repetition rate of over 250 Hz. Due to the probably pencil-shaped sonar beam, there was much variation in the amplitude of the reverberations of part of the click in the approach to the hydrophone in the centre of the pool. The 23 clicks used in the final scatter plot as typical examples of this species are from earlier careful processed click trains. The example chosen for the model fitting is shown in Figure 3.

The fourth member in the *Phocoenidae* cluster is from Alberto's non-published research on *Phocoenoides dalli* sonar behaviour at sea. Recordings were made in Monterey Bay by Kamminga, Engelson and Norris in December 1989. We observed plenty of sonar activity from this animal, when several animals approached the vessel to inspect the hydrophone, B&K type 8105. From nearby, the result was an extremely high signal-to-noise ratio of over 40 dB, as is to be seen noted in Figure 4. Pursuing literature for a description of *dalli* sonar, we note two papers, by Hattori et al. (1990) and Awrey et al. (1979). A similarity of the clicks from *dalli* with those of *Phocoena* had been noted by Kamminga (1988). Given the fact that for this species we could not rely on the previous carefully chosen material from our archives, another procedure was followed. The here-used 15 typical examples of sonar clicks were chosen from four click trains. This selection was not carried out in a random way, but samples were chosen from a persistent, stable part of the click train, i.e., we were looking for the lowest number for the relative frequency bandwidth. This method had previously been used with the varying orientation of the dolphins towards the hydrophone for a free ranging Isa (Kamminga et al., 1993).

The last cluster that is incorporated in the collection of clicks for wave shape comparison originates from the echolocation data of a free ranging *Tursiops* (Kamminga, 1990) recorded in 1986 off the Coast of Brittany, France.
Signal processing and analysis

The Vauquita signal

After a first aural detection, the previously taped *Phocoena sinus* sonar clicks were digitized at a sampling rate of 1048 kHz by a 14 bit A to D converter in the HP 3565 signal processor, and backed up by a HP9000/425 workstation. For the spectral analysis, a standard 512 point FFT was used on an interactively selected arbitrary number of data points that covered the first (main) part \( \Delta t \) of the echolocation click without including reverberations, zero-padded to the left and to the right of \( \Delta t \). This procedure has proved to be very effective in the case of odontocete clicks (Kalmijn et al., 1990). However, it is also a justified analysis method for *Phocoena* type sonar clicks as shown below. The typical waveform for a sonar click of the Vauquita is again depicted in Figure 5a. The phase change, where a reverberation follows the main pulse, is clearly visible and is used further throughout the calculation of the time envelope to indicate this main part of the click. The time duration \( \Delta t \) is conveniently taken as \( \Delta t = 2 \tau \), with \( \tau \) taken as the standard deviation of the envelope of the time function. In this manner there is more agreement about the impression as to what the time duration of a click effectively means. Further, we are dealing in general with recordings that have signal-to-noise ratios in the order of 20-40 dB, the left marker of \( \Delta t \) indicates the point where the click emerges out of the background noise. For a Gaussian curve, the number 2\( \tau \), corresponds with a probability of occurrence of 3.10\(^{-5}\). The actual time duration turns out to be a value of 70 \( \mu \) sec. The click shown in Figure 5a has a signal-to-noise ratio of 31.8 dB.

The frequency spectrum of the windowed click is presented in Figure 5b. The logarithmic scale is used to get a better impression of the dynamics in the spectrum and a better view of the frequencies surrounding the dominant frequency. Bandwidth is again defined by \( \Delta f = 2 \tau \), i.e. the standard deviation of the frequency spectrum relative to the dominant frequency, which definition differs only slightly from the currently used 3 dB value.

The next step in the processing and analysis stage of the Vauquita sonar click is the application of the parametric description of the click waveform in terms of the Gabor representation (Kalmijn et al., 1990; 1991). Emphasis in this description is laid on the features of dominant frequency (domf), time duration (\( \Delta t \)), uncertainty product (\( \Delta f \Delta t \)) and number of cycles (Nc=\( \Delta t \) domf). An important parameter for agreement as to whether the Gabor model fits the actual sonar click is given by the energy ratio of the residue to the model. A satisfactory fit would occur if the residue is similar in magnitude and dynamic behaviour to the noise preceding the pulse. If the residue is more or less similar to the noise preceding and following the click, the fit is considered to be satisfactory since further improvement is questionable. Another viewpoint on the significance of the residue could be given when we convert this figure into a signal-to-noise ratio. In doing so, we then obtain a
logarithmic measure which, when compared next to the actual signal-to-noise ratio of the actual click, indicates the difference that is left to arrive at a satisfactory fit. The analytical expression for the Gabor time function as used in the Marquardt-Levenberg fitting procedure is given by

$$f(t) = \exp\left[-\frac{t^2}{\alpha^2}ight] \cos\left(2\pi f(t-\Delta t) + \gamma\right)$$

with $\alpha = 2\pi f_0$.

A closer look at the main pulse via its envelope clearly shows an asymmetry, indicating the presence of internal reverberations, which is also indicated by the 170 kHz side lobe in the spectrum and the deviating high uncertainty product of 1.60. An attempt to fit a single Gabor pulse to the Vaquita click yields a residue of 5% that visually differs significantly from the background noise, showing the harmonic oscillation from the main part of the click. The situation is pictured in Figure 5c. If we calculate the signal-to-noise ratio of this energy residue to the main part of the click, we arrive at a value of 13 dB which given the actual S/N of 31.8 dB leaves space to reconsider our model fitting. We now take the Gabor estimation for a possible composition of several pulses, starting with modeling in a region of interest that is situated to the left-hand side of the discontinuity in the envelope. This is indicated by the arrow marker in Figure 5c. Subtracting the model from the original click leaves us not only with a residue of 0.5%, but also with a substantial part of the main click (see Figure 5d) on the right side of the point of asymmetry. Under the assumption that this part—the first reverberation—is an echo from the very first part of the main click, we can fit again the Gabor model. This modeling could easily be started with the obtained parameters of the first part. Subtracting the second Gabor from the main click then reveals that the second half of the main pulse vanishes to 0.8%, which leaves us with the result that we have obtained a decomposition of the original, asymmetric pulse into two Gabor pulses. This at first glance hidden reverberation explains the asymmetry in the overall waveform and eventually the higher uncertainty product of 1.60 for the Vaquita click. The total energy residue of the main click after the decomposition into two elementary signals is in the order of 0.7%. This residue can be explained by the fact that the reverberation outside the main pulse has its influence on the model fitting of the second Gabor pulse within $\Delta t$. The two signals and the envelope presented by their envelopes in Figure 5e. The time shift between these two Gabor pulses is 20 ps ± 0.5 ps. This value $\Delta t$ accounts for the first reverberation as an echo with the same frequency as the first part, in the very near vicinity of the sound source. The measured click values do not differ significantly from the model values. The model parameters are listed in Table 1.

Continuing our analysis, we took the Phocoena signal from Phocoena phocoena. Two typical examples are involved in the final presentation of the behavior of $\Delta t$ versus $\delta f$, the young Pacific animal $\sigma$-months-old, called Magic, and the adult North Sea by-catch animal.

The 'Magic' signal

The prominent wave shape of this young Phocoena with a time duration $\Delta t$=65 ps is presented in Figure 6a. Inspection of the envelope of the sonar click does not reveal at first sight a possible decomposition into two separate elementary waveforms; this is due to the time value of $\Delta t$, $\delta f$=1.15, which is unusually low for a polycyclic click of 8.5 oscillations. However, a closer look at the parametric model-forming shows that a building up, similar to the above-described Vaquita click, is valid. The final residue turns out to be 0.3%. The time separation between the two elementary Gabor building blocks is now 18 ps ± 0.5 ps. We note a lower amplitude of the first reverberation with regard to the Vaquita signal. The other parameters are listed in Table 1 for comparison.

The Odense signal

Proceeding along the same lines of reasoning now applied to the adult Phocoena signal, it is quite obvious to find an analogous situation of two elementary overlapping Gabor signals, shifted in time of 16 ps ± 0.5 ps that compose the sonar click. The final residue shows a value of 1.3%, which is due to the original signal-to-noise of 26.4 dB. The uncertainty product $\Delta t$, $\delta f$=1.30 points towards the possibility of a composite signal. The typical waveform is given in Figure 7a. The parameter values of Table 1 indicate the strong correlation between the two examples of Phocoena clicks.
from geographically different locations, which is numerically supported by \( \eta = 0.95 \).

The finless porpoise signal

The typical waveform of *Neophocaena phocaenoides* is shown in Figure 8. At first glance, the time representation of this click does not reveal any symmetry, which is illustrated by the smooth envelope, nor does the spectral representation show a certain amount of skewness. Taking into account the low uncertainty product \( \Delta t \cdot \Delta f = 1.5 \) for this polycyclic signal of \( NC = 8.6 \) oscillations, we should confine ourselves first to the fitting of one Gabor model. This estimation procedure then leaves us with an energy residue that remains after the model is subtracted from the actual *Neophocaena* signal of 0.12%, which equals 29 dB and means an excellent fit in the case of the signal-to-noise ratio of the click of 34 dB.

The Dial's purpose signal

The echolocation signal of free-ranging *Phocoenoides dalli* is depicted in Figure 9a, together with its spectrum that exhibits the lowest relative bandwidth, 9%, we have ever found in the family *Phocoenidae* and the dolphins in the genus *Cephalorhynchus* spp., also showing a polycyclic sound waveform. This is caused not only by the high dominant frequency of 133 kHz, which also becomes clear when looking at the unusual long click duration of 105 µs for the prominent first part. The unenhanced time duration of the *P. dalli* recorded in the Bering Sea, was also noticed by Hatakeyama & Sears (1990). The presented waveform pictured by Awbrey (1979) of the same species indicates two phase changes in the click time duration of 250 μs, a phenomenon which is also visible in the spectral representation.

Our excellent signal-to-noise ratio of 42 dB (recorded at sea) allowed us to perform a very consistent and precise model-forming and analysis of this type of click. Inspection of the envelope of the click already indicates (as in the Vaquita signal) that we could expect more than one Gabor model pulse. Careful analysis along the same lines as those above shows that the building up of this long duration click can be done by three Gabor pulses. The number of 1.30 for \( \Delta t \cdot \Delta f \) might be again an indication to search for a composite signal. The
final residual, indicating the fit of these three added-together model pulses shows an agreement of 0.03% with the actual click (Figure 9). The time shift between the first and the second pulse is 25 μs ± 0.5 μs, significantly larger than for the Vaquita click and Phocoena phocoena. A first impression of the similarity of P. sinus waveform with Neophocaena and Phocoena indicates that we should look for cross-correlation as a linear wave-shape criterion. For the correlation with Phocoena phocoena a value of 0.76 is obtained while for N. phocoenoides a value of 0.73 indicates a good agreement.

Cluster analysis
We now present our collection of data of the total of 137 actually measured clicks in a scatter plot to further explore the underlying structure of the click data. The successful modelling of the sonar clicks validates the experience-based method of the previously given selection of features in time and frequency. We then project the four-dimensional feature space of ω (related to the time duration by

Figure 8. (a) Sonar click of Neophocaena phocoenoides. Time duration of main part, indicated by Δt equals 65.5 μs. (b) Frequency spectrum of main part of click from figure 8(a) on a logarithmic scale. Note the symmetry that occurs around the dominant frequency of 30 kHz. (c) The residual after subtracting one single Gauss model, fitted over Δt from the actual click, shown together with the envelope of the model.

Figure 9. (a) Phocoenoides dalli echolocation click. Note the deviation long time duration Δt = 105 μs. The number of cycles in Δt is N = 14.5. (b) Final residual of 0.6% after fitting three elementary Gauss pulses to the main part of Δt of the sonar click. Time shift is 24 μs and 18 μs between the elementary Gauss pulses.

Δt = π(ω_0, δω, and η onto the two dimensional subspace of δω and Δt. The results of this mapping give a good insight into the data structure of various members of the Phocoenidae Family. A final remark on this type of cluster presentation is on the justification of this projection on two features. Given the minor importance of the features t_ω (the mid-epoch of the envelope) and η (phase of the dominant frequency with regard to t_ω) the intrinsic dimensionality of the complete feature space will be chiefly determined by δω and Δt. The final plot of these two highest ranking features is given in Figure 10.

Conclusions and discussion
The Phocoenoid echolocation signals, presented for cluster analysis of their highest ranking features, δω and time duration, show quite clear separation into two clusters. The Phocoena phocoena, Phocoena sinus and Neophocaena phocoenoides clicks comprise one cluster. The species Phocoenoides dalli is distinctly separated, comprising the other cluster mainly due to the feature time duration, which is more than 50% larger than the average of the Phocoenidae cluster, the longest time
duration for poly cyclic waveforms that we have ever found, and which is in fair agreement with the earlier published waveforms. Figures for time duration by Abery et al. (1979) are not comparable due to a different definition of click duration. Thus far, we note a splitting up for echolocation waveforms that is in agreement with the taxonomic division in subfamilies. It would be intriguing to compare sounds of the remainder of the Phocoenidae species; *P. spinipinnis* and *A. dioptria*. However, to date, there have been no recordings made of these rare and rarely observed species.

Similarity is still a concept that is observer related and implies a certain degree of subjectivity. However, similarity statements can be made more rigorous by applying objective measures from mathematical physics and pattern recognition. The evaluation of a partitioning of a data set into clusters, especially in the case of bio-acoustic data, should not only be based on mathematical distance measures but also have a firm connection with the original taxonomic problem. The problem treated in this article was originally formulated as whether: (1) recordings of *Phocoena sinus* sounds would conform to the Gabor model description, and (2) *Phocoena sinus* clicks would fit into a scatter plot together with earlier-described *Phocoenina* clicks.

Both questions have been adequately investigated in this research and are answered affirmatively. From Table 1 it appears that for the sample clicks presented, we do not find a large variance in the dominant frequency, nor in the time duration with only *P. dali* as an outlier with its 105 µs length.

Observing the data in the scatter plot in Figure 10, we obtain a good insight into the restricted behaviour of the dominant frequency, which ranges from 120 kHz to 143 kHz. This is in contrast with, for example, Tursiops, where more than an octave variation in dominant frequency was found (Kamminga & Beltona, 1990) at a lower range on the frequency scale. To enhance the nature of dominant click of a wild *Tursiops* is pictured on the left. This shows the nature of one of the differences in *Tursiops* sonar signals from that of *Phocoenidae*. Most clear is the difference in time duration, as *Tursiops* concentrates along a lower value of 30 µs. The difference that can be observed in figure 10 is caused by the sample frequency that presents an accuracy of 1 kHz. We are still mulling over the question as to why *P. dali* uses this extremely long duration click of 8-12 cycles. This might be just a simple method to get more energy in the transmitting beam. Probably it has also to do with the fact that *P. dali* is a pelagic animal, while the other observed members are more coastal species. However, focusing on the spectral representation, which shows a remarkable concentration around dominant frequency (relative frequency bandwidth of 9-12%) indicates
that for a detection problem the animal could rely on a fairer resolution in frequency than the other members of the Phocoenidae. It seems reasonable to attribute a certain dolphin preference for doing the signal processing in the frequency domain. It would be interesting to search for a concordance in the hearing system of this species. It is tempting, to calculate the frequency resolution constant for this long-duration click, following Woodward's definition (Woodward, 1965). However, the variance concept ('sharpness') could be used as a measure of the resolution of the spectrum when compared with the width of the envelope of the time function, thus indicating that there could be a certain preference for the Dalli dolphin to operate in the frequency domain. The location of Phocoena sinus on the scatter plot shows that the clicks of this species fit nicely in the cluster that is formed by other members of the Phocoenidae subfamily. This is further supported by the correlation factor as a shape criterion applied to N. phocoenoides and P. phocoena, giving a figure of 0.76 and 0.73, which becomes more or less visible on inspections of the typical examples of these clicks.

Finally, we are still left with the phenomenon of decomposition of the wave form of the Phocoenidae members. It is remarkable that N. phocoenoides shows to be an exception because of the symmetrical time envelope which allows one to suffice with one Cuber model, which might be indicated by the relative low number for A.M of 1.10. With regard to the other members, the difference in the time shift of the first and second Cuber pulses of the decomposition of the click are too significant to be ignored. It is tempting to indicate the time shift between the peaks as a probably morphological feature that distinguishes the species. Further research, especially in the direction of functional forehead anatomy should be carried out, preferably with modern techniques like CT and MRI tomography.

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References


