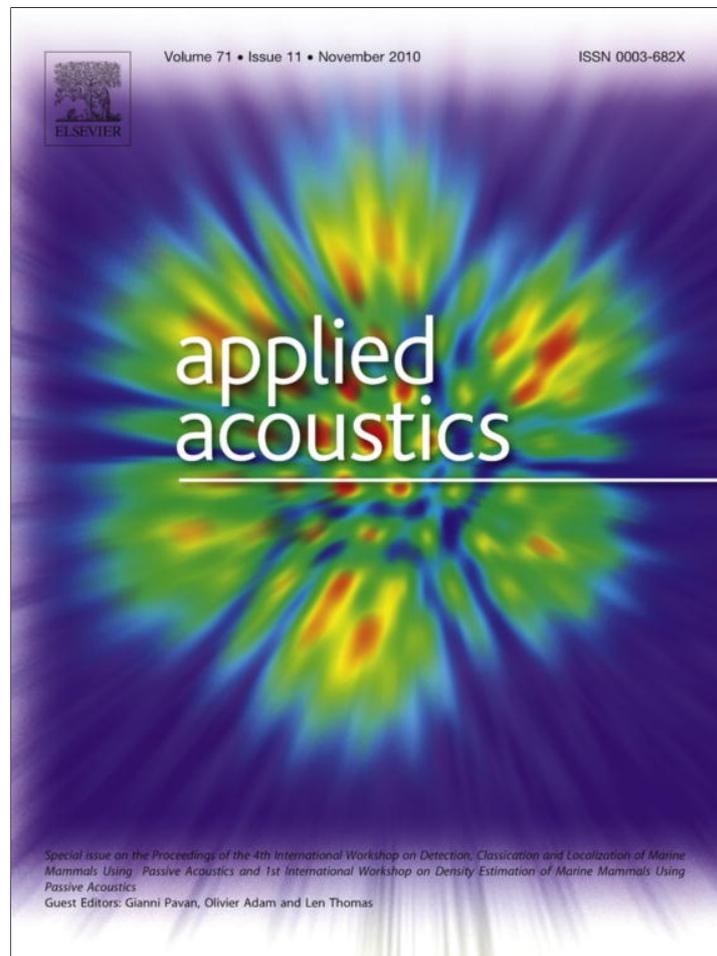


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## Performance of a contour-based classification method for whistles of Mediterranean delphinids

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### ABSTRACT

Whistles from five delphinid species in the western Mediterranean Sea (*Stenella coeruleoalba*, *Grampus griseus*, *Delphinus delphis*, *Tursiops truncatus*, *Globicephala melas*) were taken from GREC sound archives. FFT contours (window size 512, Hanning, sampling frequency 44.1 kHz) were extracted with custom developed Matlab software: 277 samples of striped dolphins (Sc), 158 whistles of Risso's dolphins (Gg), 120 of common dolphins (Dd), 76 of bottlenose dolphins (Tt), and 66 of pilot whales (Gm) were selected. Seafox software extracted 15 variables from the digitized contours, including: duration, initial, final, maximal and minimal frequency slopes, frequency range, number of frequency extrema, beginning, ending, maximal and minimal frequencies, presence of harmonics. Four of five species were significantly different (Mann–Whitney test) for average durations (respectively 0.73, 0.65, 0.47 and 0.89 s for Sc, Gg, Dd, Gm) while the average duration of bottlenose dolphins was 0.71 s. Frequency ranges (respectively 7.3, 6.3, 4.6, 3.2 and 6.3 kHz) were significantly different for all species pairs, with the exception of bottlenose and Risso's dolphins. From a global point of view, pilot whale calls were the most distinct, with 43 significant pair-wise tests out of a total of 52, followed by the common dolphins. Risso's dolphins were closest to other species whistles. A CART classification method achieved a global classification rate of 62.9%.

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### 1. Introduction

Whistles are a common part of most delphinid vocal repertoires and they may convey information on species identity, on individual and population identity, and on the behavioral state of the caller [1]. Whistles as species identifiers have an important consequence in terms of marine life management. They provide the opportunity to identify species based on their acoustic outputs, thereby allowing survey work to extend to rough sea conditions. In contrast, visual surveys rely on calm to good conditions. However, species identification from whistle emissions is not a straightforward process, since many dolphin species have repertoires with partly overlapping characteristics. For example, in the Eastern Tropical Pacific (ETP), Oswald et al. [2,3] found that striped dolphin whistles were difficult to discriminate from those of eight other delphinids, in particular common dolphins. Their classification approach involved extraction of 12 variables from whistle spectrographic contours and included two different methods, discriminant analysis and CART classification trees.

The western Mediterranean basin shelters five common delphinid species [4]: the long-finned pilot whale (*Globicephala melas*),

Risso's dolphin (*Grampus griseus*), striped dolphin (*Stenella coeruleoalba*), short-beaked common dolphin (*Delphinus delphis*), and bottlenose dolphin (*Tursiops truncatus*). Whistles are commonly emitted by all five species, and pilot whale vocalizations also routinely include pulsed calls. The aim of this study was to discriminate the whistles of Mediterranean delphinids on the basis of a simple semi-automated contour analysis and of multi-variate statistical techniques.

### 2. Materials and methods

Small boat surveys conducted by GREC in the whole Mediterranean Sea has included towed hydrophone sampling with systematic recording of good quality cetacean vocalizations since 1990. The primary data set for this study consisted of 120 whistles of common dolphins (from six sightings), 158 of Risso's dolphins (six sightings), 277 samples of striped dolphins (18 sightings), 76 of bottlenose dolphins (five sightings), and 66 of pilot whales (from eight sightings). Whistles were extracted from recordings obtained in the whole western basin, whenever possible, except those of striped dolphins, which came only from the northwestern Mediterranean basin (Fig. 1). We only used recordings obtained from single species sightings, with conditions allowing for a reliable visual

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identification of dolphin species, i.e. wind < Beaufort 3, distance < 400 m and contact of over 5-min.

Hydrophone elements were Benthos AQ-4, coupled with MAG-REC (Ltd.) preamplifiers. Although their response was flat ( $\pm 3$  dB) up to 31 kHz, only the 0.2–20 kHz bandwidth was collected, either with a Sony portable tape recorder (up to 1995), Sony TCD-7/TCD-8 Digital Audio Tape, or a Marantz PMD-670 (digital compact flash storage). The Digital Audio Tape (DAT) recordings were converted to analog format using TCD-7/TCD-8 devices and re-digitized to \*.wav files by the PC sound card. All delphinid recordings were played and stored in files of about 90 s duration, the content of which were individually described and coded in an access database. Data-base requests were performed to select relevant recordings from the 4000+ sample set, and the whistles were individually extracted from the selected 90 s recordings and stored for subsequent contour extraction. Whenever a series of similar whistles was encountered in a file, only one sample was selected for analysis.

We developed new software (Seafox) to extract 15 variables from our contours and processed data using the CART classification technique. Seafox extraction software was written in Matlab 6.0 and based on a 512 point Fast Fourier Transform of whistles sampled at 44.1 kHz, using a Hanning window with 25% overlap. This overlap ratio was chosen in order to enable comparisons of our contour extractions with those performed by TRIA, software previously developed and tested by Marc Lammers of the University of Hawaii and [2]. The initial spectrogram was obtained after running a variable threshold routine and a high pass/low pass filtering option included in Seafox software. Frequencies of highest amplitude

were then extracted from every time window and stored for contour plotting. This first extracted frequency contour could then be improved by using several software options: smoothing (based on a moving average), and an automatic or manual interpolation to suppress contour accidents, which were eventually caused by multiple simultaneous contours. An option of click removing consists in a decreasing of amplitudes based on a threshold selected from the waveform view.

Fifteen variables were extracted from each contour (Fig. 2): the duration, frequency range, number of contour inflections (slope sign change), beginning, ending, maximal and minimal frequencies, minimal, maximal, initial and final frequency slopes (computed on three or seven contour points), and number of harmonics (manually entered, starting from 0 for the fundamental).

Statistical study started with a pair-wise comparison of each variable for the five species (Mann-Whitney U-test). In a preliminary report dealing with four species [5], a discriminant analysis was used to classify whistles, however, from that experience and based on work by Oswald et al. [2,3], we decided to use the CART classification tree technique in this study. CART classification tree analysis has several advantages over other statistical techniques. First, it is a nonparametric analysis, thus not requiring data transformation, an important point since none of our variables followed a normal distribution. Second, at every node of the classification tree, all variables are considered as potential splitters, contrary to a discriminant analysis where only a subset of predictive variables are used in the classification analysis. Third, whistles with missing variable values can be included in the analysis. Fourth, the hierarchical nature of the CART classification makes it easy to implement

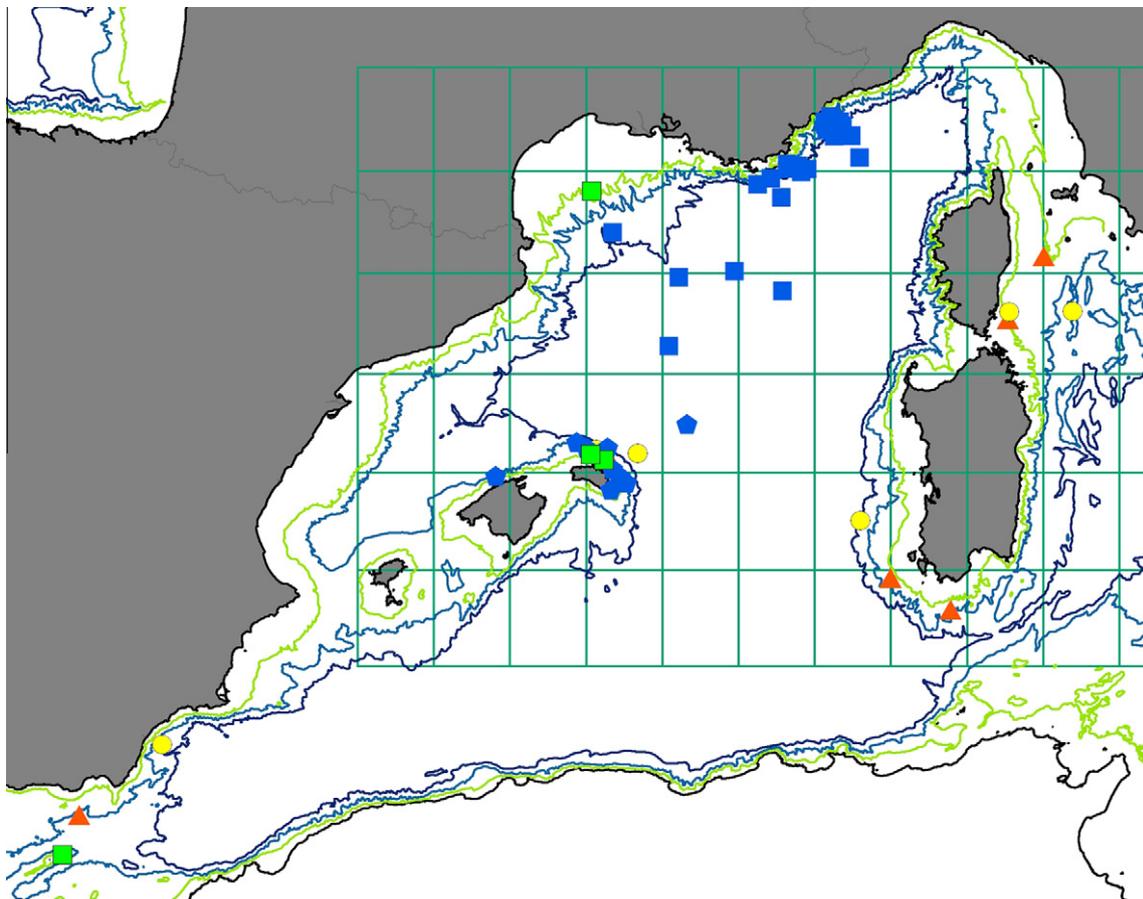


Fig. 1. Locations of recordings used for the classification study. ●: Risso's dolphin; ▲: common dolphin; ■: striped dolphin of NW basin; ■: bottlenose dolphin; ●: long-finned pilot whale.

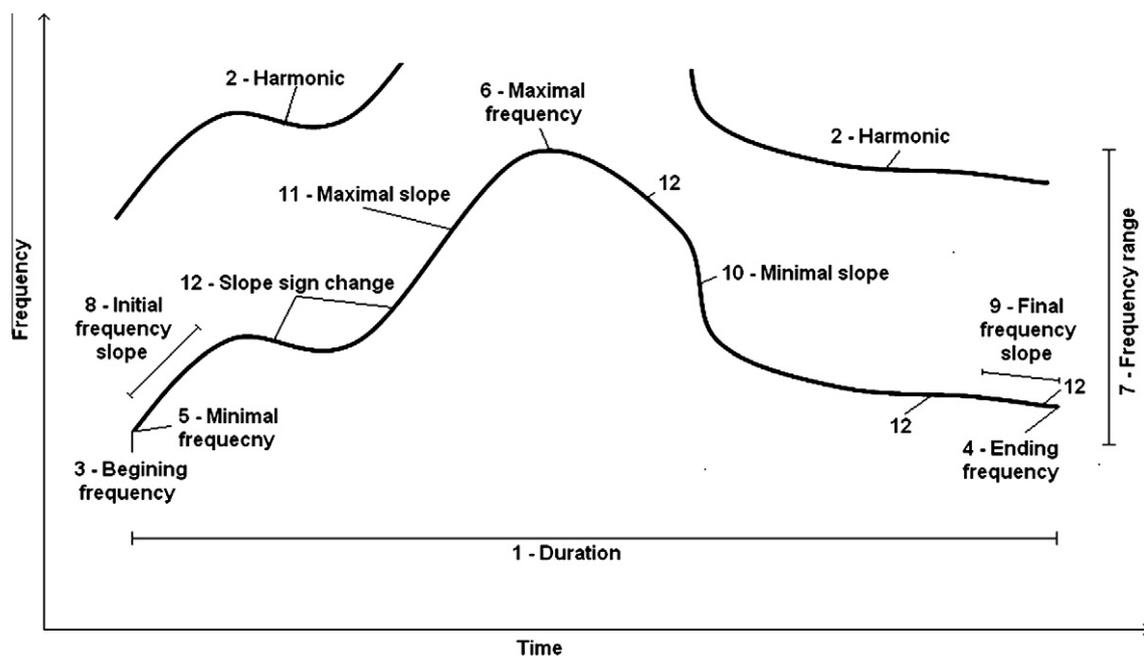


Fig. 2. Whistle contour with extracted variables.

in near real-time, and different tree options (for example to deal with different survey regions) can be easily entered in classification software. Last, during preliminary studies CART outclassed other methods in terms of the proportion of whistles correctly classified, and provided a more consistent classification rate across the different species tested [5]. Statistical testing and CART classification analysis were carried out using Statistica software ([www.statsoft.com](http://www.statsoft.com)).

### 3. Results

Seafox software enabled processing of the contours of most whistles: only 10–12% of the initial selections were rejected during the contour extraction process (for the four species of dolphins). One of the primary causes of rejection a lack of continuity, either because of a low signal-to-noise ratio or poorly defined beginning or end-points. The rejection rate increased to 30% in the case of pilot whale vocalizations, which were sometimes very confused at the beginning of a whistle. On another hand, during testing of the 15 extracted variables, the three-point beginning and ending

slopes were found to be unstable for many contours of different species: during successive contour extractions of the same whistle, values obtained for both slopes were not consistent. Both three-point slopes were consequently removed from the analysis.

#### 3.1. Descriptive statistics

Several variables showed interesting trends among the five species: whistle duration was within the same order of magnitude for all species. The average duration was less than 1 s, with the shortest value produced by common dolphins (0.47 s) and the longest value produced by pilot whales (0.89 s). On another hand, all six frequency variables were much lower for pilot whales than for the four dolphin species: the average initial and final frequencies, as well as the minimal and maximal frequencies, were about 50% lower for the pilot whale compared to the common, striped, bottlenose and Risso's dolphin (Table 1). Among these dolphins, the frequency range was lower for common dolphins (4.6 kHz) than for the other species (6.3–7.3 kHz). Mean frequency was 4.6 kHz for pilot whales, and 9.5–10.6 kHz for the smaller delphinids, hence

Table 1  
Descriptive statistics of contour variables for five species.

	Dd (n = 120) Average (SD)	Sc (n = 277) Average (SD)	Tt (n = 76) Average (SD)	Gg (n = 158) Average (SD)	Gm (n = 66) Average (SD)
Duration (s)	0.47 (0.29)	0.73 (0.35)	0.71 (0.40)	0.65 (0.36)	0.89 (0.55)
Initial frequency	10,912 (3526)	9994 (4039)	8886 (3157)	11,750 (3929)	4179 (3013)
Final frequency	11,919 (2900)	11,819 (3797)	8612 (3470)	11,877 (3522)	4909 (4181)
Minimal frequency	8527 (1942)	7868 (1843)	6421 (1684)	8287 (2027)	3195 (2256)
Maximal frequency	13,149 (2696)	15,163 (3611)	12,719 (3949)	14,652 (3270)	6384 (4400)
Mean frequency	10,475 (1827)	10,906 (2116)	9485 (2337)	10,877 (2350)	4636 (2949)
Frequency range	4622 (2738)	7296 (3543)	6297 (3957)	6365 (3244)	3189 (2893)
Initial slope (7 pts)	-18,263 (41,351)	-3024 (33,318)	21,014 (56,975)	-3806 (32,586)	3332 (24,381)
Final slope (7 pts)	14,977 (19,331)	13,222 (40,649)	644 (14,623)	19,532 (36,517)	2010 (9843)
Maximal slope	33,512 (56,968)	51,910 (90,170)	15,187 (18,715)	45,268 (61,059)	15,581 (26,014)
Minimal slope	-9412 (10,295)	-21,885 (39,396)	-16,165 (13,471)	-13,712 (19,372)	-7411 (11,249)
p Harmonics	0.19 (0.40)	0.72 (0.45)	0.62 (0.49)	0.49 (0.50)	0.88 (0.33)
k Inflections	1.1 (1.2)	1.6 (1.9)	2.1 (2.1)	1.5 (1.2)	2.1 (2.9)

Dd = common dolphin, Gg = Risso's dolphin, Sc = striped dolphins recorded in the NW basin, Tt = bottlenose dolphin, Gm = long-finned pilot whale.

**Table 2**  
Pair-wise comparisons of 13 variables for five species.

	Gm/Gg	Gm/Sc	Gm/Tt	Gm/Dd	Dd/Gg	Dd/Sc	Dd/Tt	Gg/Sc	Gg/Tt	Tt/Sc
Duration										
Number of harmonics										
Initial frequency										
Final frequency										
Minimal frequency										
Maximal frequency										
Mean frequency										
Frequency range										
Initial slope (7 pts)										
Final slope (7 pts)										
Maximal slope										
Minimal slope										
Number of extrema										

Dd = common dolphin, Gg = Risso's dolphin, Sc = striped dolphins recorded in the NW basin, Tt = bottlenose dolphin, Gm = long-finned pilot whale. Grey filling indicates significant differences at 95% confidence level (Mann–Whitney U-test).

a poor discrimination power for the common, striped and Risso's dolphins (U-test,  $p > 0.18$ ). However, the four dolphins could also be distinguished from each other based on the slope variables: for example, striped dolphin contours exhibited both the highest maximal slope (average maximal upsweep of 51.9 kHz/s) and the highest negative slope (average downsweep of  $-21.9$  kHz/s). Additionally, the bottlenose dolphin was the only species to display a strong initial upsweep (average = 21.0 kHz/s). Maximal and minimal slopes were in general lower for the pilot whale than for the other species, meaning that frequency modulations were more progressive in pilot whale whistles (U-test,  $p < 0.05$  whatever the species). On the contrary, common dolphins generally showed a strong initial downsweep (Table 1). The final contour slope of bottlenose dolphin whistles were generally weak (average = 644 Hz/s), compared to the three other dolphin species. The average visible harmonics count (up to 20 kHz bandwidth) was significantly higher for pilot whales (0.88) than for the four other delphinids examined in this study, and was lowest for common dolphins (0.19). The number of slope inflections was lower for common dolphins (1.1) than for the other species (1.5–2.1), indicating that whistles of this species were less modulated and more often monotonic than those of the other species (Table 1).

### 3.2. Pair-wise comparisons

The potential for species classification was further demonstrated by systematic pair-wise comparisons of the contour variables (Table 2). On the basis of 13 tested variables, pilot whale whistles were significantly different in 43 cases out of 52 (four pair-wise comparisons for each of the 13 classification variables). Among the four smaller delphinids, the Risso's dolphin whistles were not significantly different from those of common, striped and bottlenose dolphins in 21 comparison cases out of 39 (three pair-wise comparisons of 13 classification variables). Common dolphin whistles were significantly different from those of striped and bottlenose dolphins in 22 cases out of 26 (two pair-wise comparisons of 13 classification variables). This overview of single variable differences among the species indicated that every species' whistles had the potential to be discriminated from the other species, however with variable degrees of confidence. Not a single variable was significantly different for every species pair-wise comparison (Table 2). However, four variables were distinctive in almost all comparison cases: the number of harmonics, the minimal and maximal frequencies, and the frequency range, which was efficient to discriminate species, with  $p$ -values  $< 0.02$  except for the Risso's/bottlenose dolphin comparison (U-test,  $p = 0.51$ ). The number of inflections points was a statistically significant variable only for

the common dolphin whistles compared to the three other dolphin species. Minimal and maximal frequencies were usually significantly different in species pair-wise comparisons (U-test,  $p < 0.05$ ), except for common dolphin whistles (Table 1).

### 3.3. CART classification

The frequency range was removed from the set of potential predictive variables, because it was a second order variable derived from the maximal and minimal frequencies for each whistle. The optimal classification tree consisted of 14 terminal nodes, with 13 segmentation stages (Fig. 3) and produced an overall correct classification score of 62.9%: 259 whistles out of 694 were misclassified. Minimal frequency was used in four different segmentations. This tree provided the best trade-off between number of variables (10) and predictive power. The 10 variables that were included were: minimum frequency, presence of harmonics, average frequency, beginning frequency, duration, maximum frequency, end frequency, initial slope, and maximal slope. Correct classification scores for individual species ranged from 37.3% for Risso's dolphins to 75.5% and 79.8% for pilot whales and striped dolphins, respectively (Table 3). All classification scores were significantly better than the 20% expected by chance alone ( $\chi^2$  test,  $p < 0.05$ ).

## 4. Discussion

### 4.1. Classification efficiency

Overall, and for each of the five species, the correct classification rate was significantly better than chance (20%). Our correct classification rate varied from good (pilot whale, striped dolphin, common dolphin) to medium (bottlenose dolphin) or even poor (Risso's dolphin): in the latter case more Risso's dolphin whistles were classified as striped dolphins (39.9%) than as Risso's dolphins (37.3%). This kind of result is not exceptional: for example, striped dolphins of the ETP were more frequently classified as pan-tropical spotted and long-beaked dolphins than as the correct species [2]. This may be due to the fact that the variables included in the classification algorithms were not the optimal variables for species identification. The variables included by Oswald et al. [2] and others, Steiner [6], Rendell et al. [7] have a high degree of variability within-species and overlap among-species. These characteristics make it difficult to separate species in multi-variate space. To address this possible short-coming, we introduced a set of slope variables, but this addition did not avoid frequent misclassifications for one of our species. In fact, for all slope variables, Risso's dolphin

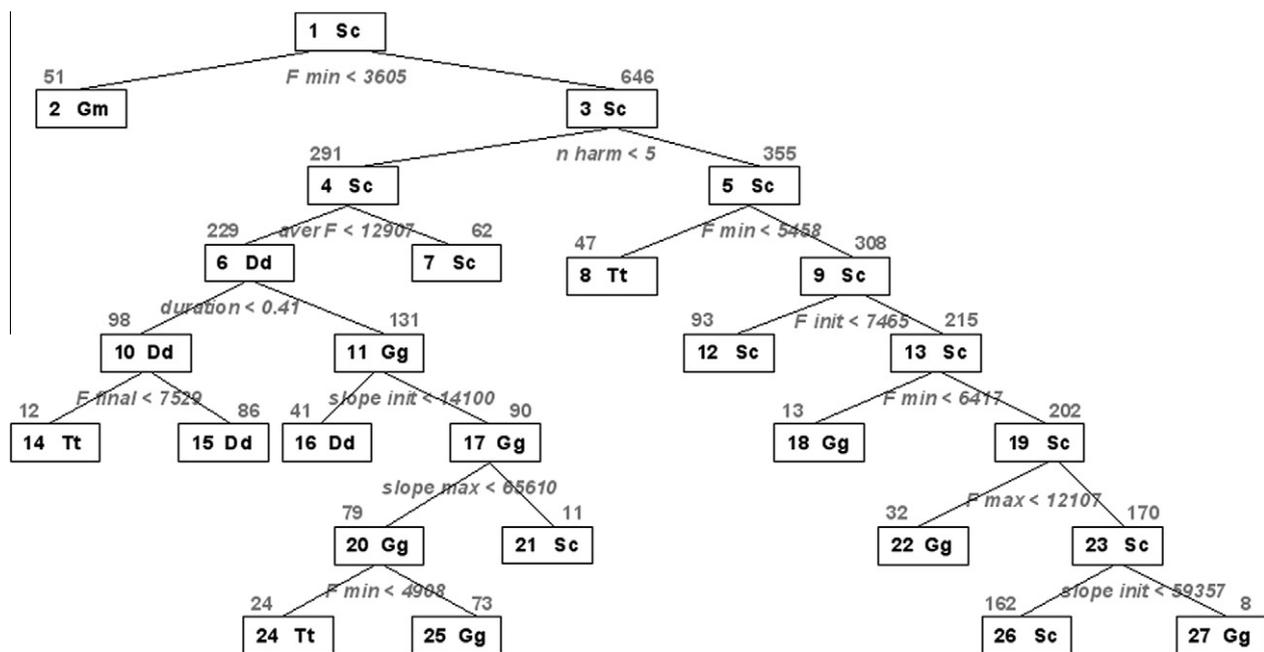


Fig. 3. CART classification tree.

**Table 3**  
Confusion matrix in percentages.

% classified as ...	Pilot whale	Common dolphin	Risso's dolphin	Striped dolphin	Bottlenose dolphin
Pilot whale	<b>75.7</b>	3	9.1	3	9.1
Common dolphin	0	<b>60.8</b>	15.0	20.8	3.3
Risso's dolphin	0	18.3	<b>37.3</b>	39.9	4.4
Striped dolphin	0.4	5.1	10.1	<b>79.8</b>	4.7
Bottlenose dolphin	0	11.8	19.7	22.4	<b>46.1</b>

Percent of whistles correctly classified for each species is in bold.

whistles were not significantly different from those of striped dolphins (Table 2). Future work on acoustic species identification should include exploration of additional variables with lower within-species and higher among-species variability.

Risso's dolphins can be identified on the basis of their unique pulsed sound emissions, the analysis of which was not possible with our software. To include different categories of sounds in their classification of four delphinid species encountered off Southern California, Roch et al. [8] used a gaussian mixture of cepstral features. They performed their classification on sound segments of longer duration, and included both tonal whistles and pulsed sounds. Roch et al. [8] obtained higher classification rates than we did here. Their data sets for two of the species were limited to recordings obtained on only three occasions, which may have reduced the diversity of sampled whistles relative to the actual species repertoire.

Since the initial study of dolphin species discrimination based on differences in whistle vocalizations [6], a number of papers have outlined the potential for using whistles to accurately identify cetacean species. Rendell et al. [7] compared the whistles of five delphinids, including both species of pilot whales, the false killer whale (*Pseudorca crassidens*), Risso's dolphin, and the white-beaked dolphin (*Lagenorhynchus albirostris*). Rendell et al. observed that species were poorly discriminated based on duration, as was the

case in this study, and that whistles were better discriminated based on frequency variables. Rendell et al. also remarked that intra-specific variation between different regions was significant, and that some variance could be attributed to the social and behavioral context of the recording. The geographical variation of whistle repertoires was also studied by Baron et al. [9] for distinct populations of pilot whales, bottlenose and Atlantic spotted dolphins (*Stenella frontalis*). These authors observed that significant differences existed between the coastal and the offshore ecotypes of spotted dolphins, and between bottlenose dolphins inhabiting the Gulf of Mexico and the nearby Atlantic Ocean. On the contrary, both pilot whale populations seemed to share the same repertoire. Hence, both papers suggest that significant differences in whistle repertoires exist for distinct populations of a given species, even at scale less than 1000 km. Consequently, classification models built with data from a limited spatial extent may not be reliable outside the restricted boundaries of the sampling area. Our present model relied on 5–18 sightings (depending on the species) obtained in a wide area of the western Mediterranean: its predictive power and robustness may still be increased by adding whistles from recordings obtained in other behavioral and social contexts.

Data sets not covering a wide range of social and behavioral circumstances may not produce robust classification models. Rendell et al. [7] showed that call duration and number of inflections had low inter-specific and high intra-regional variances, suggesting that such variables may convey information on individuals or groups, and on behavioral states. On the contrary, frequency variables had high inter-specific and low intra-regional variances, and may therefore be not as strongly related to behavior state or individual identification. As a result, these variables are more suitable for species classification models. Among frequency variables, our results showed that minimal, maximal and frequency ranges were the more significant single variables for the discrimination of species (Table 2). With the exception of the pilot whale, minimal and maximal frequencies were in a restricted range, 6.4/8.5-kHz and 12.7/15.1-kHz for the minimum and maximum, respectively, but these variables featured low standard deviations (Table 1), which is important for species identification. Oswald et al. [3] showed that minimal frequencies were poor discriminators for

similar-sized dolphins or odontocete whales, and maximal frequencies were slightly more distinct. In the present study, average frequency ranges were distinctive, except for one pair of species, although they had higher variances. Frequency range was also a distinctive variable for the whistles analyzed by Oswald et al. [2], and differences were important even for delphinids of similar size. However, Rendell et al. [7] showed that frequency range was highly variable between regions for a single species. Contrary to our anticipation, slope variables were not very powerful for the discrimination of species, as they featured high variances. A possible explanation for these high variances is that slope variables may reflect school behavioral contexts. Further study is required to determine how whistle structure relates to behavioral states. It may be that different sets of whistle variables are good candidates for species identification in different geographic locations.

#### 4.2. Sympatry and repertoire divergence

We note that striped and common dolphins could be discriminated in the Mediterranean Sea (Table 3) while they could not in the Eastern Tropical Pacific (ETP), Oswald et al. [2,3]. Using CART analysis, we were able to correctly classify 60.8% of common dolphin whistles and 79.8% of striped dolphin whistles. While common dolphin whistles were misclassified as striped dolphins more commonly than as any other species, this only occurred for 20.8% of whistles. Striped dolphin whistles were rarely misclassified as common dolphins (Table 3). Oswald et al. [3,10] found that correct classification of whistles produced by striped and common dolphins in the ETP was not significantly greater than chance ( $\chi^2$  test,  $\alpha = 0.05$ ). However, their discriminant function analyses indicated that correct classification was significantly greater than chance ( $\chi^2$  test,  $\alpha = 0.05$ ) when classifying whistles of common or striped dolphins to study area (Mediterranean vs. ETP). Hence in certain cases, differences between regions for a given species are greater than differences between species in a given region. We hypothesize that this may be related to the degree of sympatry in the two study areas. Steiner [6] found that the differences in whistle structure were greater between sympatric species than they were between allopatric species. He suggested that whistles may contain species-specific cues and that selection pressures against hybridization may have led to divergence in whistle structure among sympatric species. This can be considered a form of behavioral reproductive isolation. In the relatively recent past, striped and common dolphins were sympatric in the NW Mediterranean. Since the early 1970s, common dolphins have suffered a decline and are now absent in several portions of their former range [11,12], reducing the degree of sympatry between the two species. However, this time scale is likely not significant when considering the evolution of whistle structure and the distinctiveness in whistle structure between these two species may be related to their historical degree of sympatry. In contrast to the Mediterranean, areas where striped and common dolphins are abundant in the ETP are spatially separated with only a few exceptions [13]. In another example from the ETP, pan-tropical spotted and spinner dolphins have a high degree of sympatry and their whistles were not often confused one with each other [2,3]. The limited cases available in our study do not prove the influence of species sympatry on repertoire divergence, but they clearly confirm that whistle identification must be considered in a wide population context.

In the southwestern Mediterranean, striped and common dolphins are commonly observed in mixed schools. Such cases were encountered during our surveys and provided data unsuitable for this study. These aggregations, whatever their stability over time, also represent a challenge for an *in situ* implementation of whistle classification techniques. In some areas, such as the Eastern and Central Tropical Pacific Ocean, mixed species schools are frequent

enough that the ability to process them as a specific category would be a great advantage [2,14].

#### 4.3. Recording bandwidth

It may seem ill-fated to propose a study on delphinid whistle classification and to use recordings limited to the 20-kHz bandwidth. Oswald et al. [15] showed that broader-band analyses were useful for the classification of four small delphinids. Four spectrograms, each with a different upper frequency limit (20, 24, 30, and 40-kHz) were created for each whistle in a large data set. Then, eight variables (beginning, ending, minimum and maximum frequency; duration; number of inflection points; number of steps; presence/absence of harmonics) were measured from the fundamental frequency of each whistle. The authors observed that the whistle repertoires of all four species contained harmonic frequencies extending above 20-kHz. They showed that overall correct classification ranged from 30% for the 20-kHz upper frequency limit data to 37% for the 40-kHz upper frequency limit data. Oswald et al. [15] concluded that an upper bandwidth limit of at least 24 kHz was required for an accurate representation of whistle contours of these small delphinids. Very few whistles were discarded from their data set because the fundamental was partly out of the 20-kHz range, and all variables except the number of harmonics were extracted from the fundamental contour. In our case, the harmonic counts were strongly influenced by the 20-kHz bandwidth, because the pilot whale had a much lower average fundamental frequency than the dolphins (4636 Hz against over 10,000 Hz), and hence featured higher harmonic counts. Most or all of the harmonics will be above 20 kHz for whistles with higher fundamental frequencies. However, common, striped and Risso's dolphin whistles were all high-pitched, but showed significantly different harmonic counts (Table 2), suggesting this variable was useful for classification even for a limited bandwidth.

Different studies suggest that better classification scores could be reached in the Mediterranean Sea if broadband data were available for analysis [15]. But full broadband devices are perhaps not as useful for the study of whistles as they are for the study of high frequency clicks. For whistle studies, a sampling rate of 96 kHz might certainly be a good compromise in terms of data storage and analysis potential. It may be added that very high frequency whistle components tend to fade during sound propagation because of absorption losses, the effect being already significant between 20 and 48-kHz [16]. Therefore, using ultra high frequency sampling rates for whistle classification may be of limited practical interest for distant dolphin detections.

## 5. Conclusion

Passive acoustic monitoring methods are being increasingly used to monitor marine mammal distribution and abundance over wide oceanic areas. They are also efficient techniques to be implemented for the mitigation of adverse effects of anthropogenic activities. Our study contributes to the progress needed for the implementation of acoustic survey systems. For acoustic surveys, it is important to discriminate different odontocete species that are acoustically present but not visually available. Our present results also outline the necessity of understanding how and why species or population repertoires are driven closer or farther one from each other. When generalized acoustic identification software is used, it may not match the repertoires encountered regionally. The performance of such software may be strongly constrained by the amount of data used to create the classification model, in terms of geographic location, school diversity and behavioral context.

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## References

- [1] Au WWL, Popper AN, Fay RR. Hearing by whales and dolphins. Springer Handbook of Auditory Research; 2000.
- [2] Oswald JN, Barlow J, Norris TF. Acoustic identification of nine delphinid species in the Eastern Tropical Pacific Ocean. *Mar Mammal Sci* 2003;19:20–37.
- [3] Oswald JN, Rankin S, Barlow J, Lammers MO. A tool for real-time acoustic species identification of delphinid whistles. *J Acoust Soc Am* 2007;122:587–95.
- [4] Gannier A. Summer distribution and relative abundance of delphinids in the Mediterranean Sea. *Rev Ecol (Terre Vie)* 2005;60:223–38.
- [5] Gannier A, Fuchs S, Gannier O, Oswald JN. Pelagic delphinids of the Mediterranean Sea have different whistles. In: 23rd Conference of the European cetacean society (Istanbul, 2–4 March 2009), Abstracts 40.
- [6] Steiner WW. Species-specific differences in pure tonal whistle vocalizations of five western North Atlantic dolphin species. *Behav Ecol Sociobiol* 1981;9:241–6.
- [7] Rendell LE, Matthews JN, Gill A, Gordon JCD, Macdonald DW. Quantitative analysis of tonal calls from five odontocete species, examining interspecific and intraspecific variation. *J Zool Lond* 1999;249:403–10.
- [8] Roch MA, Soldevilla MS, Burtenshaw JC, Henderson EE, Hildebrand JA. Gaussian mixture model classification of odontocetes in the Southern California Bight and the Gulf of California. *J Acoust Soc Am* 2007;121:1737–48.
- [9] Baron SC, Martinez A, Garrisson LP, Keith EO. Differences in acoustic signals from delphinids in the western North Atlantic and northern Gulf of Mexico. *Mar Mammal Sci* 2008;24:42–56.
- [10] Oswald JN, Gannier A, Rankin S, Fuchs S, Barlow J. Differences in whistle characteristics of two delphinid species in the Eastern Tropical Pacific Ocean and Mediterranean Sea. In: Second international conference on acoustic communication by animals, Corvallis, Oregon, 12–15 August; 2008.
- [11] Forcada J, Hammond P. Geographical variation in abundance of striped and common dolphins of the western Mediterranean. *J Sea Res* 1998;39:313–25.
- [12] Bearzi G, Agazzi S, Gonzalvo J, Costa M, Bonizzoni S, Politi E, et al. Overfishing and the disappearance of short-beaked common dolphins from western Greece. *Endang Species Res* 2008;5:1–12.
- [13] Reilly SB. Seasonal changes in distribution and habitat differences among dolphins in the Eastern Tropical Pacific. *Mar Ecol Prog Ser* 1990;66:1–11.
- [14] Rankin S, Barlow J, Oswald J, Ballance L. Acoustic studies of marine mammals during 7 years of combined visual and acoustic line-transect surveys for cetaceans in the eastern and central Pacific Ocean, NOAA-TM-NMFS-SWFSC-429; 2008. 69pp.
- [15] Oswald JN, Rankin S, Barlow J. The effect of recording and analysis bandwidth on acoustic identification of delphinid species. *J Acoust Soc Am* 2004;116:3178–85.
- [16] Au WWL, Hastings M. Principles of marine bioacoustics. Springer; 2008.