


# First report of signature whistles in an oceanic common bottlenose dolphin (*Tursiops truncatus*) population from Revillagigedo Archipelago, Mexico

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## Abstract

This study is the first baseline acoustic description of common bottlenose dolphin populations (*Tursiops truncatus*) from Revillagigedo Archipelago and the first identification of signature whistles (SWs) in an oceanic population of *T. truncatus*. A total of 85% (199/233) of the recorded whistles were classified as stereotyped whistles and subsequently (bout analysis/SIGID) categorized into one of five SW types. External observers were in perfect agreement in classifying whistles into the adopted SW categorization. SWs represented 42% (98/233) of the repertoire. Overall, most whistle types were categorized as sine (80%; SW1, SW2, SW4, and SW5) with one downsweep (20%, SW3). Roca Partida Island had the highest number of SW types. Principal component analysis explained 77% of the total SWs variance, highlighting the importance of shape/contour variables to the SWs variance. The combined mean SWs acoustic parameters from Revillagigedo Archipelago were higher than that recorded in coastal regions, which may indicate there are differences between SWs of pelagic and coastal populations. However, further acoustic and ecological studies in the Archipelago are needed to clarify and expand our findings, to identify its members (Photo ID and

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SW Revillagigedo Catalog), and to investigate this topic at other oceanic islands.

**KEYWORDS**

acoustic repertoire, bioacoustics, bottlenose dolphins, marine mammals, Revillagigedo, signature whistles, Socorro Islands, *Tursiops truncatus*, whistles

## 1 | INTRODUCTION

Common bottlenose dolphins (*Tursiops truncatus*) produce a wide variety of vocal signals typically divided into broadband echolocation clicks, broadband burst pulses, and frequency-modulated narrowband whistles (Jones et al., 2020a). Tonal whistles are easily categorized and measured and have therefore been the most studied dolphin vocalization (Janik & Sayigh, 2013; Jones et al., 2020b; Wang et al., 1995). According to Harley (2008), dolphin whistles are easily recognized vocalizations because they are narrowband, fairly loud, and have a relatively low frequency that can reach individuals up to 25 km away if the sea conditions are good and the signal output ranges from 3.5 to 10 kHz (Janik, 2000).

Any type of identity signal that might indicate the presence of dolphins or the motivational state of individuals is of value since it may enhance the recognition of kin, mates, allies, and facilitate social interactions (Luís et al., 2016), especially in a fission-fusion society apparently built upon the maintenance of long-term social ties (Wells, 1991, 2003). While most animal species use morphologically determined voice features to recognize the call sender (Rendall et al., 1998), bottlenose dolphins use learned individually distinctive frequency contours (Janik & Sayigh, 2013). These personalized acoustic signals are called signature whistles (SWs) and express identity information (Caldwell et al., 1990; Sayigh & Janik, 2010).

Melba and David Caldwell (Caldwell & Caldwell, 1965) first identified and described for the first time these distinctive vocalizations in captive bottlenose dolphins. Their results were questioned (McCowan & Reiss, 1995a, 1995b, 2001), but further study has confirmed their interpretation of the data (Janik et al., 2013; Marino et al., 2007; Sayigh et al., 2007). As a result of these evaluations, hundreds of captive and free-living bottlenose dolphins have had their SWs registered and successfully cataloged (Caldwell & Caldwell, 1965; Caldwell et al., 1990; Esch et al., 2009; Harley, 2008; Janik, 1999, 2009; Janik et al., 1994; Janik & Slater, 1998; Janik et al., 2006; Kriesell et al., 2014; Luís et al., 2016; Sayigh et al., 1995, 2007; Watwood et al., 2005). Based on those studies, it is possible to conclude that SWs are frequency-modulated vocalizations issued in a repetitive pattern capable of transmitting the sender's identity to its surrounding. Specifically, these whistle vocalizations are (1) individually distinct, (2) stable throughout life (crystallized), (3) dominant among whistles, (4) produced when animals are isolated or out of visual contact with their conspecifics, and (5) developed during the first months of life. The development of whistle includes the learning process of vocal production and is based on an individual's auditory social experiences (Caldwell & Caldwell, 1965; Esch et al., 2009; Fripp et al., 2005; Janik & Sayigh, 2013).

The relative stability and dominance of the SW repertoire of a bottlenose dolphin have provided researchers an accessible way to understand the communication and the cognitive mechanisms of this mammal group (Janik et al., 2013). However, the available information on SWs is almost exclusively derived from captive or inshore/coastal bottlenose dolphin populations (Harley, 2008; Heiler et al., 2016; Jones et al., 2020b; King & Janik, 2013; Kriesell et al., 2014; Longden et al., 2020; Luís et al., 2016; Papale et al., 2015; Rachinas-Lopes et al., 2017; Sayigh et al., 2017; Terranova et al., 2021). Information about the SWs of oceanic populations of common bottlenose dolphins is still limited and little is known about the ecology of these populations (Silva et al., 2008).

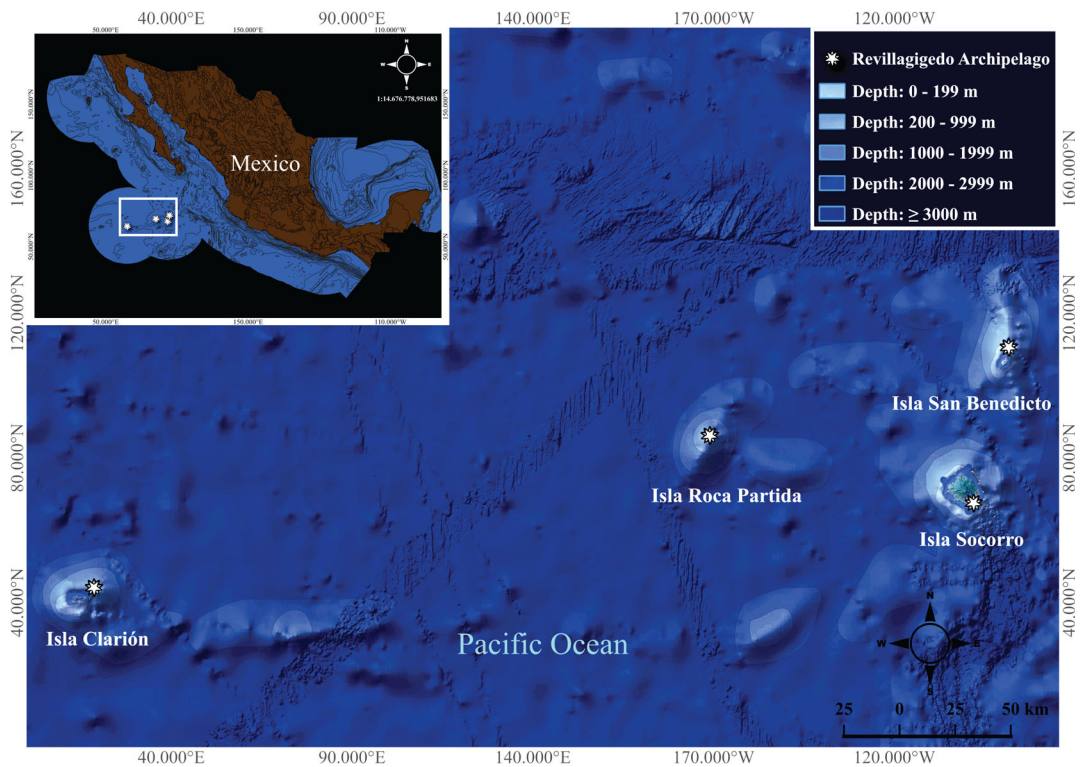
This study aims to record the acoustic vocalization and to identify and categorize the SWs of an oceanic population of the common bottlenose dolphin *T. truncatus* from the Revillagigedo Archipelago, Mexico.

## 2 | MATERIALS AND METHODS

### 2.1 | Study site

Acoustic data were collected during 7 days (December 28, 2020 to January 3, 2021) at three of the four islands (San Benedicto, Socorro Island, and Roca Partida Island) of the remote Revillagigedo Archipelago, in the Mexican Pacific (Figure 1).

The Revillagigedo Archipelago is located in the eastern Pacific Ocean inside the Exclusive Economic Exclusive of Mexico, approximately 390 km southwest of the southern tip of the Baja California Peninsula and 720 km to the west of the mainland Mexico (World Heritage Committee, 2016). The Revillagigedo Archipelago has a rich marine diversity and is considered an important stopover point for wide-ranging species (World Heritage Committee, 2016). The Archipelago is part of a submarine mountain ridge. Its four islands represent the peaks of volcanoes emerging above sea level. The islands comprise 148,088 km<sup>2</sup> (Diario Oficial de la Federación, 2017) of protected area only inhabited by two small naval bases. Areas between 10–12 km from the islands shore can abruptly reach depths of



**FIGURE 1** Map of the study area in the Revillagigedo Archipelago islands, Mexico, eastern Pacific Ocean, with the bathymetry and landform data from the four islands that comprise the archipelago: San Benedicto Island, Socorro Island, Roca Partida Island, and Clarión Island. Acoustic recordings of sounds produced by oceanic population of the common bottlenose dolphin (*Tursiops truncatus*) were obtained throughout the archipelago. Clarión Island was not included.

up to 3,700 m due to their volcanic origin, particularly to the west of Roca Partida Island and to the west and south of Clarión Island.

## 2.2 | Acoustical recordings and analysis

All data were collected from a liveaboard vessel (33.5 m length, 7.5 m width, capacity 30 people) with engines turned off, anchored at permitted areas surrounding each of the islands (permission N°. SGPA/DGVS/00823/20). Other ships were present during the data sampling but never exceeded a maximum of three ships per island. The acoustic recordings were taken continuously. Daytime visual confirmation of *T. truncatus* was obtained throughout 7 days and recorded the presence of up to 11 individuals sighted four times, twice from boat observations and twice during SCUBA exploration activities.

Underwater recordings were conducted with a Hydrophone System BuninTech H0220 (final sensitivity with gain of 52 dB from GainBox:  $-152$  dB re 1 V/uPa  $\pm 3$  dB; frequency band: 5 Hz–80 kHz) placed at a depth of 5 m and connected by a 10 m cable to a Tascam DR-100MKIII digital recorder. Recordings were made at a sample rate of 96 kHz and 24-bit resolution. All acoustic data were stored in 5 min recording files (with no time gap between consecutive files) stored in a 256 Gb secure digital card (SD) flash memory cards as time-stamped wave files.

Here we use the term “whistle” to describe a tonal sound with a fundamental narrow-band frequency of over 0.1 s duration (Evans & Prescott, 1962; Lilly & Miller, 1961) with at least part of the fundamental frequency above 3 kHz (Simard et al., 2011; van der Woude, 2009). This vocalization has been recognized as an uninterrupted (single-element or connected multiloop whistle) or two or more repeated contours (disconnected multiloop whistle) interrupted by very short breaks (0.03–0.25 s) (Esch et al., 2009; Kriesell et al., 2014).

All whistles with good signal-to-noise ratio (Papale et al., 2013) and with complete and clear spectral contours were manually selected for the analysis performed in the spectrogram viewer of Raven Pro 1.6.1 (Cornell Laboratory of Ornithology, Ithaca, NY) with 1,024 fast Fourier transform size (FFT), Hanning window, and 50% overlap.

The term “whistle type” is used to ascribe all whistles of a particular frequency modulation pattern or contour into predetermined categories following human visual evaluation (Janik, 1999; Sayigh et al., 2007).

Whistle categories containing repeated units produced at least twice within a period of 0.25–10 s during a recording section were classified as stereotyped whistles (STW; Kriesell et al., 2014; Luís et al., 2016). Interwhistle intervals (IWI) were calculated subtracting the end time of the first whistle from the start time of the second whistle in the recording file. Nonstereotyped whistles (NTW) refer to whistles emitted individually or separated by more than 10 s.

The emission sequence of whistles and their IWIs were analyzed using the SIGnature IDentification (SIGID) method (Janik et al., 2013). The SIGID method identifies SWs using single-hydrophone recordings of unrestrained bottlenose dolphins (Janik et al., 2013) and has provided an easy way to learn about individually distinctive whistles using a bout analysis approach to identify SWs in recordings of freely interacting animals (Kriesell et al., 2014).

SWs were identified according to STW categories with at least four whistles. Therefore, if at least once during the sequential bout analysis, 75% or more of the whistles occurred within 1–10 s of another whistle of the same category, it was considered a SW type (Janik et al., 2013). Whistle classification was made by one experienced observer and subsequently cross-validated by another observer. All NTW and those STW that did not fill the SIGID criteria were defined as non-SWs for our analysis.

To confirm that different SW categories were reliably identified, a visual similarity value judgment was performed based on the evaluation of five naive independent observers that had no previous experience with bioacoustics experiments. These observers based their judgments on a randomly chosen data subset, following the methodology of Jones et al. (2020b) and Kriesell et al. (2014). Six whistle replicates of each one of the five SW types were previously and randomly selected for the task. One of the replicates acted as a template whistle and the remaining five were classified by the observers. Using a Microsoft PowerPoint presentation, a sequential survey was

created with each one of the 25 whistle repetitions at the slide center surrounded by the five SW templates. Each whistle was plotted as a spectrogram (1,024 FFT, Hanning window and 50% overlap) with standardized time and frequency axis (frequency y-axis: 0–25.0 kHz; time x-axis 0–5.0 s, scales not plotted). The configuration of the template whistles did not change between slides, but the order of the presentation was randomized for each observer. For the first part of the task (the preliminary phase), observers were asked to compare each whistle replicate against all five templates and rate the similarity of each whistle replicate on a scale from 1 (the whistle and the template are very different) to 5 (the whistle and the template are very similar). This resulted in a total of 125 pairwise comparisons. During the binary second part of the task the observers were constrained to assign each whistle replicate to a single “most similar” template category. The observers were instructed to ignore other details such as whistle amplitude and background noise and the presence or absence of harmonics (i.e., repetitions of the whistle contour at multiple frequency intervals above each contour). The first author of this publication (RR), who created the STW catalog and classified the SWs, also completed the task.

To characterize the whistles, the following acoustic and temporal variables were measured for all SW types: starting frequency (StaF), ending frequency (EndF), minimum frequency (MinF), maximum frequency (MaxF), frequency bandwidth (BanF), whistle duration (Dur), interwhistle interval (IWI), interloop interval (ILI), and number of inflections points (InfP) (change from positive to negative aspect or vice versa) (Kriesell et al., 2014). BanF, MinF, MaxF, and Dur were automatically measured in Raven, while the other parameters (StaF, EndF, InfP, IWI, and ILI) were manually measured or counted.

Whistle copies are rare and normally can be recognizable as such because copiers consistently modify some acoustic parameters of a signal when copying it (King et al., 2013). However, when whistle copying was identified, it was not clear whether the copy was the first or second overlapping whistle, the second whistle (i.e., the one that overlapped) was assumed to be the copy and was removed from all analyses (Kriesell et al., 2014).

## 2.3 | Statistical analyses

Descriptive statistical analysis and the Shapiro-Wilk test were performed for all independent variables. According to the normality test, none of the acoustical or temporal data have a normal distribution.

The emission rate of non-SWs (STW and NTW) and SWs per location was calculated by dividing the number of whistles by the minutes of recorded whistle time. The recorded whistle time was defined as the interval between the first and last acoustic signal of dolphins (clicks or whistles) either if there was or was not visual confirmation.

The Fleiss's Kappa statistics (calculated with and without the author classification) was used to compare the ratings among observers and to determine interobserver agreement and consistency in SW categorization. If observers were in perfect agreement in their classification, then Fleiss' kappa statistic ( $\kappa$ ) is equal to 1.00 (Landis & Koch, 1977). If agreement amongst observers was the same as would be expected by chance (i.e., the absence of agreement), then  $\kappa = 0.00$ .

A principal component analysis (PCA) using a correlation matrix of the acoustic parameters and temporal patterns (StaF, EndF, MinF, MaxF, BanF, Dur, IWI, ILI, and InfP) as independent variables was performed to reduce data to a new set of independent principal components (PCs) and elucidate which parameters contribute most to SWs variability. Before that, data were z-scored/normalized by subtracting averages and dividing by the standard deviation. Z-scoring is a common method used to normalize data. The matrix was rotated using varimax rotation, which attempts to minimize the variance of squared loadings for each factor and improves interpretability of the variables (Jolliffe, 2002). The factorial adequacy Kaiser-Meyer-Olkin (KMO) test was used to select the number of components (linear combinations of the original variables) to be kept for the analysis, excluding all PCs with an eigenvalue lower than one (Jolliffe, 2002). Thus, any component that explained a lower variance than an original variable in the correlation matrix was excluded. A coefficient of correlation linking old and new variables was calculated and all variables

were plotted in a three-dimensional space. The KMO measurement of 0.523 ( $>0.5$ ) and the Bartlett's test of sphericity ( $p < .001$ ) justified the use of PCA.

All statistical analyses were performed using IBM SPSS Statistics (SPSS Software Inc., Chicago, IL) and GraphPad 8 (GraphPad Software Inc., San Diego, CA) at a 95% level of significance.

### 3 | RESULTS

#### 3.1 | Descriptive analyses

Acoustic recording time, whistle classification, and emission rate are displayed in Table 1. The recording effort time was relatively well distributed among the evaluated locations, although San Benedicto Island had twice the recording time compared to the others (San Benedicto Island: 1,924.87 min = 50.47%; Socorro Island: 983.87 min = 25.80%; Roca Island Departure: 904.92 min = 23.73%). This result was probably due to the location of this island being chosen as the arrival and departure point for the expedition to the Revillagigedo Archipelago.

A total of 63 hr 32 min 59 s of acoustic recordings was used for analysis. The whistle time recorded represented less than 6% of the recording effort time (5.54% in Roca Partida Island and less than 1.49% and 1.37% in Sao Benedicto Island and Socorro Island, respectively). A total of 233 whistles were extracted from the recorded time, from which 85.41% (199/233) were classified as STW. The remaining 14.59% (34/233) of whistles were considered NTW. A total of 49.25% (98/199) of STWs were clearly classified as SWs by the bout criteria of the SIGID method (Janik et al., 2013). These SWs that were classified according to the five SW types and the number of samples per SW type ranged from eight (SW4) to 36 (SW1). SWs represented 42.06% (98/233) of all analyzed whistles, with an emission rate of 1.062 SW/min of the total recorded whistle time. The San Benedicto Island showed the highest emission rate (3.880 whistles/min) among all locations, while Roca Partida Island concentrated 60% (3/5) of SW types identified in the Archipelago.

Figure 2 represents the STW contours that were positively categorized into five types of SWs (SW1, SW2, SW3, SW4, and SW5) and examples of spectrograms showing the variation in SW5. Overall, most whistle types were classified as sine (wavering sinusoidal whistles: 4/5 = 80%; SW1, SW2, SW4, and SW5), while the final SW was classified as a downsweep (1/5 = 20%; SW3).

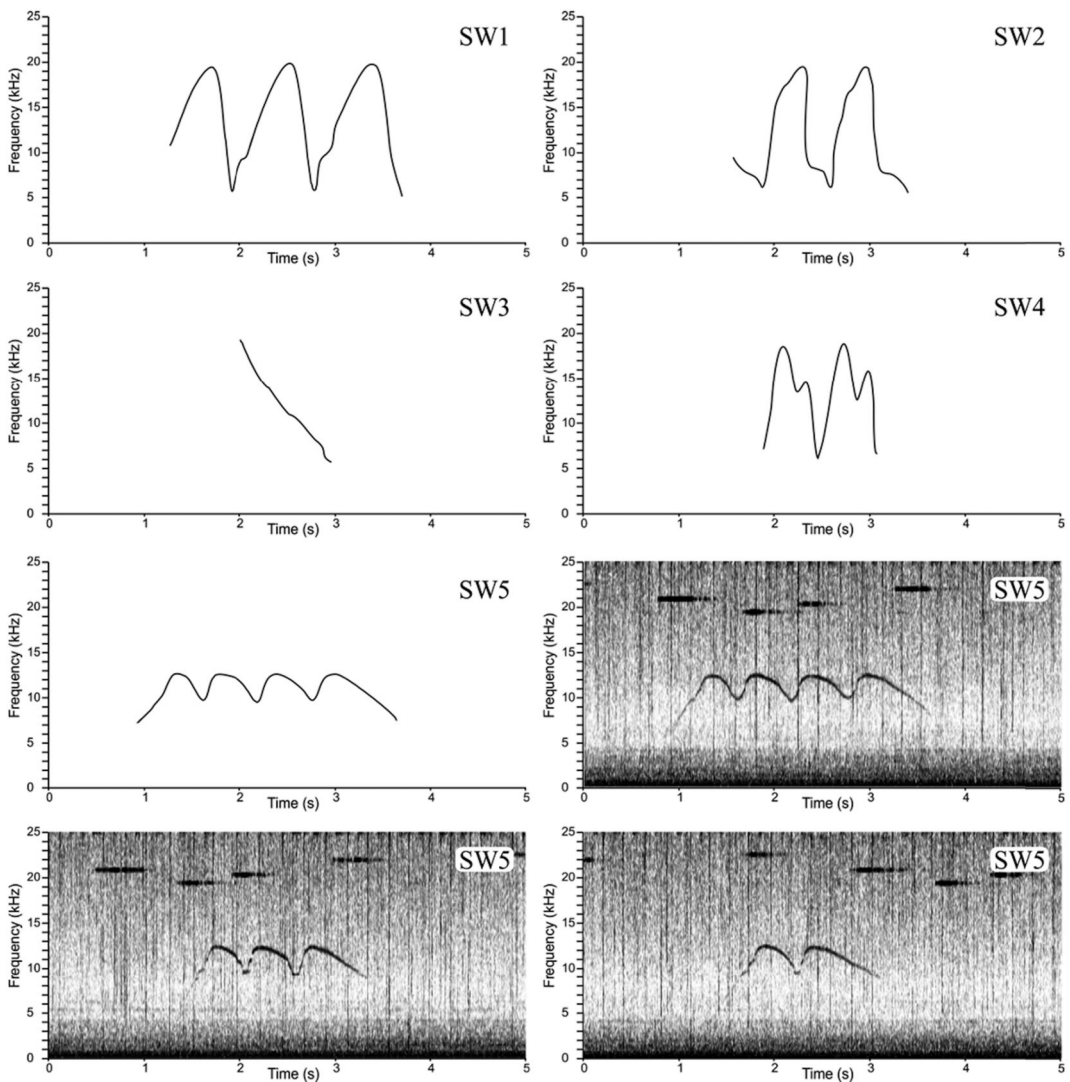
#### 3.2 | Acoustic parameters

Mean values and standard deviation (SD) of acoustic parameters of each SW type are described in Table 2. Number of samples per SW type ranged from 8 (SW4) to 36 (SW1). The mean values of EndF and MinF were similar to each

**TABLE 1** Acoustic recording time, whistle classification, and emission rate produced by an oceanic population of the common bottlenose dolphin (*Tursiops truncatus*) from the Revillagigedo Archipelago, Mexico.

Location (Island)	Recording effort time (hh:mm:ss)	Recorded whistle time (hh:mm:ss)	Whistle classification			Total
			SW (n)/ER	STW (n)/ER	NTW (n)/ER	
San Benedicto	32:04:52	00:28:52	1 (36)/1.247	10 (59)/2.044	12 (17)/0.589	23 (112)/3.880
Socorro	16:23:52	00:13:36	1 (11)/0.809	2 (5)/0.368	2 (2)/0.147	5 (18)/1.324
Roca Partida	15:04:55	00:49:50	3 (51)/1.023	10 (37)/0.742	8 (15)/0.301	21 (103)/2.066
Total	63:32:59	01:32:18	5 (98)/1.062	22 (101)/1.094	22 (34) /0.368	49 (233)/2.524

Note. Signature whistles (SW); stereotyped whistles (STW; SWs not included); nonstereotyped whistles (NTW); n = number of recorded samples; ER = emission rate obtained by dividing the number of the whistles by the recorded whistle minutes.



**FIGURE 2** Representative contours of five signature whistle (SW) types (SW1, SW2, SW3, SW4, and SW5) and examples of SW5 spectrograms identified for an oceanic population of the common bottlenose dolphin (*Tursiops truncatus*) from the Revillagigedo Archipelago, Mexico, by the SIGID method. Frequency (kHz) is on the y-axis and ranges from 0 to 25 kHz. Time (s) is on the x-axis and represents 5 s. The scaling is the same for all items. Corel Draw X7 was used to extract the outline of the whistles. Spectrogram settings: fast Fourier transform size = 1,024, Hanning window, overlap = 50%. The numbers at the top right corner of each item represents the identification numbers of each SW type.

other for most SW types, with values within 2 kHz for most whistles except for SW4 (5 kHz). The downsweep contour of SW3 had the highest StaF mean (18.71 kHz) of all identified categories. SW2 and SW5 had the lowest MaxF means (around 13 kHz), while the other types were close to 19 kHz.

Bandwidth was a fluctuating acoustic parameter, with a pooled mean value of 10.14 kHz for all SW types, ranging from 4.90 kHz (SW5) to 13.45 kHz (SW1). The SW type duration had a pooled mean value of 1.49 s, with the longest mean SW of 2.05 s (SW5) and the shortest mean SW of less than half this value (0.94 s for SW3). Following the logic of bout emission, the longest (SW5) and shortest (SW3) SW types were also the ones that had the longest

**TABLE 2** Mean  $\pm$  standard deviation of acoustic parameters of the five signature whistle (SW) types ( $n = 98$ ) produced by an oceanic population of the common bottlenose dolphin (*Tursiops truncatus*) from the Revillagigedo Archipelago, Mexico.

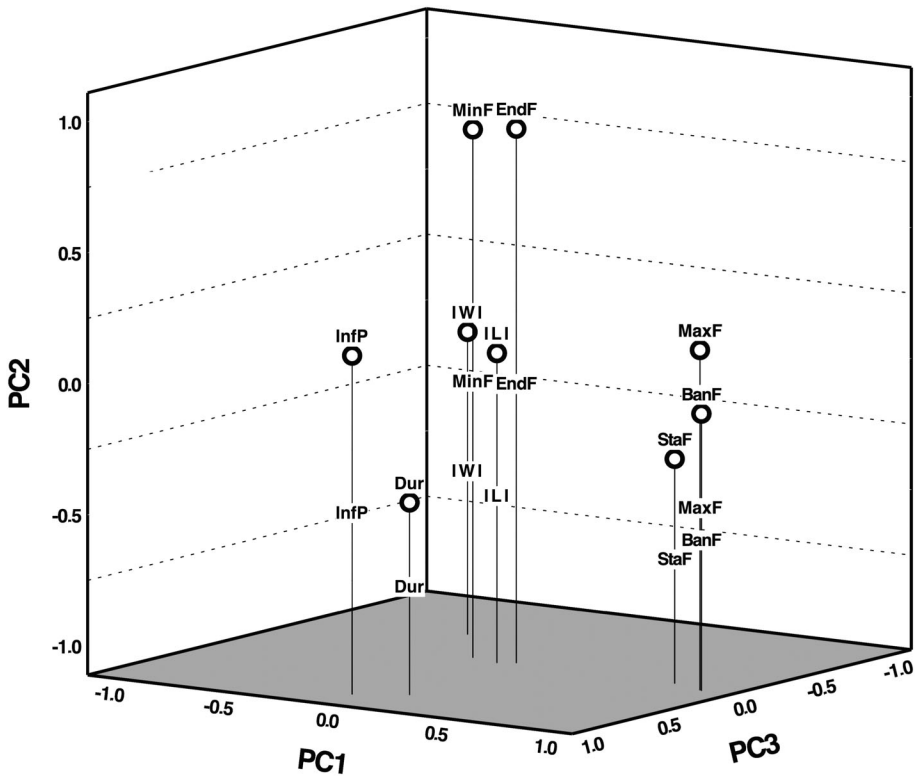
ID	<i>n</i>	Frequency (kHz)					Shape			
		Start (StaF)	End(EndF)	Minimum (MinF)	Maximum (MaxF)	Bandwidth (BanF)	Duration (s) (Dur)	Interwhistle (s) (IWI)	Interloop (s) (ILI)	Inflection (n) (InfP)
SW1	36	13.33 $\pm$ 1.99	8.88 $\pm$ 2.95	7.37 $\pm$ 0.63	20.82 $\pm$ 0.25	13.45 $\pm$ 0.74	2.00 $\pm$ 0.56	1.99 $\pm$ 1.45	0.30 $\pm$ 0.05	4.75 $\pm$ 1.57
SW2	11	11.72 $\pm$ 0.92	6.29 $\pm$ 1.040	6.29 $\pm$ 1.04	13.54 $\pm$ 3.00	7.25 $\pm$ 3.41	1.52 $\pm$ 0.19	3.13 $\pm$ 0.92	0.46 $\pm$ 0.07	4.18 $\pm$ 0.60
SW3	22	18.71 $\pm$ 2.55	8.53 $\pm$ 1.681	8.24 $\pm$ 0.70	19.00 $\pm$ 1.58	10.75 $\pm$ 1.66	0.94 $\pm$ 0.14	1.66 $\pm$ 0.99	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00
SW4	8	10.75 $\pm$ 1.69	13.56 $\pm$ 2.94	8.99 $\pm$ 0.39	20.22 $\pm$ 0.39	11.22 $\pm$ 0.64	1.42 $\pm$ 0.23	3.60 $\pm$ 3.76	0.51 $\pm$ 0.12	8.00 $\pm$ 2.44
SW5	21	8.09 $\pm$ 1.06	8.39 $\pm$ 0.81	7.71 $\pm$ 0.73	12.62 $\pm$ 0.07	4.90 $\pm$ 0.71	2.05 $\pm$ 0.38	4.05 $\pm$ 2.20	0.30 $\pm$ 0.05	5.66 $\pm$ 1.31
Total	98	13.03 $\pm$ 4.08	8.79 $\pm$ 2.70	7.65 $\pm$ 0.98	17.79 $\pm$ 3.68	10.14 $\pm$ 3.64	1.49 $\pm$ 0.87	2.55 $\pm$ 2.01	0.35 $\pm$ 0.10	4.08 $\pm$ 2.74



**TABLE 3** Principal components analysis (PCA) loadings (correlations between variables and components) of varimax-rotated PCA of the acoustic and temporal variables of five signature whistle (SW) types ( $n = 98$ ) produced by an oceanic population of the common bottlenose dolphin (*Tursiops truncatus*) from the Revillagigedo Archipelago, Mexico.

Variables	Principal component (PC)		
	PC 1	PC 2	PC 3
Minimum (MinF)	0.434	0.045	<b>0.782</b>
Maximum (MaxF)	0.082	<b>0.947</b>	0.236
Duration (Dur)	<b>-0.858</b>	0.322	-0.205
Bandwidth (BanF)	-0.078	<b>0.975</b>	-0.048
Start (StaF)	<b>0.845</b>	0.211	-0.204
End (EndF)	-0.026	0.011	<b>0.909</b>
Inflection (InfP)	<b>-0.890</b>	0.212	0.041
Interwhistle (IWI)	<b>0.537</b>	0.113	0.182
Interloop (ILI)	0.188	-0.438	<b>-0.567</b>
% Variance	30.73	24.99	21.51
Cumulative %	30.73	55.72	77.23

Note. Bold values are statistically significant. Variables which are highly loaded on the same component are strongly related.



**FIGURE 3** Principal components analysis (PCA) results in a three-dimensional space identified by PCs (PC1, PC2, and PC3) in which acoustic and temporal variables of five signature whistle (SW) types ( $n = 98$ ) produced by an oceanic population of the common bottlenose dolphin (*Tursiops truncatus*) from the Revillagigedo Archipelago, Mexico. Variables are distributed forming different clusters according to their correlations.

(4.05 s) and shortest (1.66 s) IWI, respectively. ILI and InfP ranged from absent in linear whistles (SW3) to 0.51 s and 8.0 s, respectively, in SW4. The highest number of InfP was observed in the SW4 samples, which more than once presented up to 11 points of inflection in a single contour.

### 3.3 | Visual classification

The first stage of the judgment task (preliminary task of rating the similarity of each repeat whistle on a scale from one to five) showed a fair/minimal interobserver agreement (Landis & Koch, 1977) both without (K-Fleiss = 0.292, IC 95% 0.264, 0.320;  $z = 20.352$ ,  $p < .001$ ) and with (K-Fleiss = 0.376, IC 95% 0.353, 0.399;  $z = 31.975$ ,  $p < .001$ ) the first author as an observer. In contrast, in the second stage of the task (the binary phase of assigning each whistle to a single “most similar” SW type category) the results showed a perfect interobserver agreement both without (K-Fleiss = 0.968, IC 95% 0.880, 1.056;  $z = 21.645$ ,  $p < .001$ ) and with (K-Fleiss = 0.973, IC 95% 0.902, 1.045;  $z = 26.656$ ,  $p < .001$ ) the first author as an observer.

### 3.4 | Multivariate analysis

The PCA reduced the nine recorded SW acoustic and temporal production parameters to three independent PCs. This explained 77.23% of the total variance of individually distinctive whistles of bottlenose dolphins from the Revillagigedo Archipelago. The canonical loadings showed that InfP, Dur, StaF, and IWI were the most correlated parameters within PC 1 (variance = 30.73%), while BanF and MaxF were strongly correlated in PC 2 (variance = 24.99% variance). In PC 3, EndF, MinF, and, ILI had a contribution of 21.51% of the total variance. Table 3 shows the loadings of the varimax-rotated PCA of the SW acoustic and temporal variables produced by the dolphin population of the Revillagigedo Archipelago. Figure 3 shows the three-dimensional space identified by PCs in which the variables are distributed throughout different clusters according to their correlations.

## 4 | DISCUSSION

A SW is a learned, individually distinctive whistle, issued in a bout pattern of a unique frequency modulation contour that allows conspecifics to associate this unique sound to the individual that produced it. The SW conveys an outline to identify the whistler, allowing individual recognition inside a group and therefore maintaining contact and cohesion (Caldwell & Caldwell, 1965; Esch et al., 2009; Janik & Sayigh, 2013).

The identification of stereotyped and nonstereotyped whistles and their emission context in wild coastal and deep oceanic populations is a critical step toward a better understanding of these distinctive calls (Luís et al., 2016). Of the main scientific publications on SWs of wild bottlenose dolphins, more than half were conducted in the same coastal geographic region, in Sarasota Bay, Florida (Cook et al., 2004; Esch et al., 2009; Fripp et al., 2005; Janik et al., 2006; Kershenbaum et al., 2013; King et al., 2013; Sayigh et al., 1990, 1995, 2007, 2017; Watwood et al., 2005). Others studies were conducted in four different coastal locations in Portugal (Luís et al., 2016), Namibia (Heiler et al., 2016; Kriesell et al., 2014; Longden et al., 2020), Italy (Papale et al., 2015; Terranova et al., 2021), and Scotland (King & Janik, 2013; Quick & Janik, 2012).

Bottlenose dolphin populations of coastal/inshore regions are more susceptible to anthropogenic underwater noise than animals from oceanic habitats, which can influence their vocalizations (Heiler et al., 2016; van Ginkel et al., 2018). Underwater noise can modulate whistle signals of individual dolphins and favors changes in signal transmission, a phenomenon known as acoustic adaptation (Ansmann et al., 2007; Bittencourt et al., 2017; Luís et al., 2021; May-Collado & Wartzok, 2008; Morisaka et al., 2005).

Because the Revillagigedo Archipelago is a protected area with limited visitation policies, it differs from other coastal regions previously evaluated. Its bathymetry characteristics do not allow the simultaneous anchoring of more than four vessels per island. Moreover, the surroundings of island regions (narrow platform) can have deep waters. The bioacoustics and many basic ecological characteristics of *Tursiops truncatus* from the Revillagigedo Archipelago are unknown. This is the first study to collect acoustic information and SWs of oceanic populations of this species. This endeavor will allow future studies to expand the knowledge about the vocalizations of the dolphins at this location.

Roca Partida Island had the lowest recording effort, but the highest number of SW types and recorded whistle time; it also had the second highest whistle emission rate. These results suggest that this island is a spot for dolphins and should be considered in future acoustic expeditions. However, many factors that influence the whistle emission rate were not evaluated in this study, including behavior, group size, calf presence, anthropic actions, and stress level (Briefer, 2012; Esch et al., 2009; Jones & Sayigh, 2002; Kriesell et al., 2014; May-Collado, 2013; May-Collado & Quiñones-Lebrón, 2014; Quick & Janik, 2008). The SW emission rates vary widely according to behavioral context (Cook et al., 2004), thus other studies focusing on acoustic monitoring should be conducted and will help to better clarify this matter.

The fact that none of the five identified SW types have been registered in more than one location does not provide evidence that the existence of different populations in each of the islands. We must consider the short acoustic recording time and the lack of scientific information about the possible size and profile of the existing populations around the Revillagigedo Archipelago. Empirical estimates suggest approximately 300 individuals of *T. truncatus* are distributed throughout the Archipelago area (H. R. Nanduca, personal communication, November 16, 2021). In addition, the short distance between San Benedicto and Socorro islands would allow dolphins to move between these islands. This assumption is based on the extensive movements reported for the coastal/offshore ecotype populations of *T. truncatus*, an average of 89 km per day (Wells et al., 1991). On the other hand, the predictable increase in primary production and fish aggregations near areas with steeply sloping benthic topography, such as shelf breaks and seamounts (Fiedler, 2002; Klatsky et al., 2007; Rogers, 1994), could influence the preference for residency at a specific island. Although there are no acoustic (SWs) and visual data to conclude whether the same individuals are using more than one location around the Revillagigedo Islands, this does not mean they are completely isolated. Additional research is needed to characterize the dolphin populations around the Revillagigedo Archipelago, identify individuals (Photo ID and SW Revillagigedo Catalog), and understand the gene flow and the use of local habitat.

The high proportion of STW identified [85.41% (199/233)] in this study and its subsequent assignment rate to SWs [49.25% (98/199)] was an expected outcome and could even be higher considering that the SIGID is a conservative criteria with a success rate of 50% and no possibilities of false positives (Janik et al., 2013). During the classification phase in a study in coastal Namibia, Kriesell et al. (2014) registered a total of 69.49% (918/1,321) of clear contours as STW. These contours were also assigned to one of the 28 SW types (89.33% [820/918]) by SIGID and have between 6 and 81 SWs per type. SWs represented half of the overall identified whistle contours recorded for coastal bottlenose dolphins inhabiting the Pelagos Sanctuary in Italy (Terranova et al., 2021). Cook et al. (2004) found that 52% of whistles produced by undisturbed wild dolphins in Sarasota Bay, Florida, were signature or probable SWs. All three of these results are similar to those found for the Revillagigedo Islands, where SWs represented 42.06% of all whistles analyzed.

Based on our results and over 50 years of dedicated research about SWs by different research groups, from Sarasota (Cook et al., 2004; Esch et al., 2009; Fripp et al., 2005; Janik et al., 2006; Kershenbaum et al., 2013; King et al., 2013; Sayigh et al., 1990, 1995, 2007, 2017; Watwood et al., 2005) and Scotland (King & Janik, 2013; Quick & Janik, 2012), it appears that nearly 50% of coastal and ocean bottlenose dolphin whistles produced by free-ranging animals in the wild are SWs. Although this percentage may vary from 38% to 70% in free-living dolphins (Buckstaff, 2004; Cook et al., 2004; Janik & Sayigh, 2013; Watwood et al., 2005), it can reach up to almost 100% in animals isolated from their conspecifics (Caldwell et al., 1990; Janik & Slater 1998; Sayigh et al., 2007).

Overall, the pooled mean acoustic parameters and temporal SWs production recorded in oceanic Revillagigedo dolphins were consistent with the few studies that have also been conducted using pooled data (Kriesell et al., 2014; Terranova et al., 2021). However, a more detailed analysis revealed that except for the ending frequency (EndF), all other parameters had higher values for the Revillagigedo Islands when compared to coastal studies performed in Italy (Terranova et al., 2021) and Namibia (Kriesell et al., 2014). These are the values from our survey, from Namibia, and Italy, respectively: MinF—7.65 kHz, 5.97 kHz, and 5.06 kHz; StaF—13.03 kHz, 7.32 kHz, and 8.02 kHz; MaxF—17.79 kHz, 13.70 kHz, and 13.54 kHz; BanF—10.14 kHz, 7.73 kHz, and 8.49 kHz; (Dur—1.49 s, 1.24 s, and 1.44 s; InfP—4.08, 2.54, and 1.4; and ILI —0.35 s, and 0.14, not evaluated in Italy). Even including the EndF, the pooled mean recorded in our survey (8.79 kHz) was lower than previous records in Italy 9.50 kHz (Terranova et al., 2021), but higher than the observed in Namibia (6.42 kHz) (Kriesell et al., 2014). A previous comparative study between the whistle acoustic parameters of a coastal and an oceanic population of bottlenose dolphins in Brazil also showed that EndF was the only parameter of the oceanic population that was lower than the coastal one, although the authors did not differentiate SWs from non-SWs (Hoffmann et al., 2012). Even so, the EndF of 8.44 kHz recorded for animals sighted in the surrounding oceanic waters of the Saint Peter Saint Paul Archipelago (Hoffmann et al., 2012) was lower than that of the oceanic population of the Revillagigedo Archipelago (as well as all the other spectral and temporal parameters) and higher than the coastal populations considered (Kriesell et al., 2014; Terranova et al., 2021).

Altogether, the high mean values of frequency parameters (MinF, StaF, MaxF, and BandF) may indicate that there are differences for SWs between pelagic and coastal bottlenose dolphin populations as a result of environmental acoustic adaptation (La Manna et al., 2020; Luís et al., 2021) and/or definitive acoustic changes (cultural drift or gene flow) (La Manna et al., 2017; Lima et al., 2020; Papale et al., 2014). Signals emitted by an animal are adapted to the environment it lives in to minimize degradation, maximize signal transmission, and ensure long-range communication (Ey & Fischer, 2009). The high intraspecific variability in the recorded frequency modulation (average number of InfP), Dur, and ILI could reflect the transmission of personal (SW) information and, potentially, emotional state (Norris et al., 1985; Steiner, 1981; Wang et al., 1995). Conversely, the low number of SW types identified here, and the low number of total SW samples, may have influenced the descriptive mean data comparisons, so more SW identifications from different pelagic populations are needed to confirm these data.

ILI, IWI, and InfP are parameters that are influenced by the SW contour which allowed a generic joint analysis of the contour shape rather than a separate parameter analysis. The SW types registered in the Revillagigedo Archipelago were mostly emitted as single/continuous whistle types (100%; not discontinued), especially as a multiple or multiloop shape (80%). This corroborates previous findings from coastal SW populations (Esch et al., 2009; Kriesell et al., 2014; Terranova et al., 2021). It is important to highlight that SW types can be emitted as entire or partial contours and sometimes only the introductory, intermediate, or terminal portion of the signal is produced as we registered in our study (Figure 2; see also Tyack, 1986).

External observers that had no previous experience with bioacoustics studies confirmed our visual SW classification for the dolphin populations of the Revillagigedo Archipelago. The relatively fair/minimal agreement recorded at the first stage of the visual classification task, either without (K-Fleiss = 0.292,  $p < .001$ ) or with (K-Fleiss = 0.376,  $p < .001$ ) the first author as an observer, was higher than the agreement found by Kriesell et al. (2014; K-Fleiss = 0.216,  $p < .001$  and K-Fleiss = 0.238,  $p < .001$ , without and with the first author as an observer, respectively). This suggests that the SW frequency modulation patterns may not be particularly distinct at this preliminary classification phase of interobserver agreement. The preliminary phase of visual agreement involves subjective score assignments (one to five), which naturally tends to have lower agreement between raters. Conversely, the classification agreement amongst observers in the second stage of the visual classification task was considered perfect, either without (K-Fleiss = 0.968,  $p < .001$ ) or with (K-Fleiss = 0.973,  $p < .001$ ) the first author as an observer. The agreement rate of this second stage was higher than other studies that used a similar experimental design, without and with the first author as an observer, respectively (K-Fleiss = 0.693,  $p < .001$  and with K-Fleiss = 0.630,  $p < .001$ , Terranova et al., 2021) or only without the first author as an observer (K-Fleiss = 0.848,  $p < .001$ , Kriesell

et al., 2014). Although the small number of SW types may have facilitated the judgment, the high agreement level in whistle classification emphasizes the reliability of our findings and supports our categorization.

Based on the results of three different PCA tests, 77% of the total variance of individually distinctive bottlenose dolphins whistles from the Revillagigedo Archipelago was explained, corroborating the expected 70%–90% range (Jolliffe, 2002). The canonical loadings showed that InfP, Dur, StaF, and IWI were the most correlated acoustic values for the first principal component, indicating the importance of shape/contour variables for the variance of SWs. This result corroborates other studies that suggest that bottlenose dolphins respond to SWs produced by familiar conspecifics after voice features were removed (Janik et al., 2006). This reinforces the notion that a SW contour carries identity information (Janik et al., 2006) and not acoustic parameters (Sayigh et al., 2007). Conversely, previous research that used PCA analysis and SWs explained similar numerical percentage magnitudes (82% of the total variance) with three PCs, but highlighted MaxF, MinF, and mean frequency as the most important parameters to distinguish SWs (Terranova et al., 2021).

## 4.1 | CONCLUSIONS

Our results revealed the occurrence and importance of SWs in the acoustic repertoire of an oceanic population of bottlenose dolphins, whose spectral and temporal results may indicate that there are differences of SWs between pelagic and coastal populations. In this sense, the acoustic variability could represent an adaptation to environmental acoustic conditions and/or definitive acoustic changes (cultural drift or gene flow). However, further acoustic and ecological studies in the Archipelago are needed to clarify and expand our findings, to identify its members (Photo ID and SW Revillagigedo Catalog), and to investigate this topic at other oceanic islands.

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## AUTHOR CONTRIBUTIONS

**Raul Rio:** Conceptualization; data curation; formal analysis; investigation; methodology; project administration; resources; supervision; validation; visualization; writing – original draft; writing – review and editing. **Hiram Rosales-Nanduca:** Writing – review and editing. **Lucia A. Piuma:** Data curation; formal analysis; writing – review and editing. **João F. Piuma:** Data curation; formal analysis. **Manuela Piuma:** Data curation. **Guilherme S. Redecker:** Writing – review and editing. **Lilian S. Hoffmann:** Validation; writing – review and editing.

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