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Abstract: By-catch is the most direct threat to marine mammals globally. Acoustic repellent devices (pingers) have been developed to reduce dolphin by-catch. However, mixed results regarding their efficiency have been reported. Here, we present a new bio-inspired acoustic beacon, emitting returning echoes from the echolocation clicks of a common dolphin '*Delphinus delphis*' from a fishing net, to inform dolphins of its presence. Using surface visual observations and the automatic detection of echolocation clicks, buzzes, burst-pulses and whistles, we assessed wild dolphins' behavioural responses during sequential experiments (i.e., before, during and after the beacon's emission), with or without setting a net. When the device was activated, the mean number of echolocation clicks and whistling time of dolphins significantly increased by a factor of 2.46 and 3.38, respectively ($p < 0.01$). Visual surface observations showed attentive behaviours of dolphins, which kept a distance of several metres away from the emission source before calmly leaving. No differences were observed among sequences for buzzes/burst-pulses. Our results highlight that this prototype led common dolphins to echolocate more and communicate differently, and it would favour net detection. Complementary tests of the device during the fishing activities of professional fishermen should further contribute to assessment of its efficiency.

Keywords: bio-acoustics; etho-acoustic; cetaceans; echolocation; clicks; whistles; buzz; burst-pulse; sound processing; Bay of Biscay

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1. Introduction

Fishery by-catch is the main direct cause of mortality of marine mammals worldwide with an estimated 600,000 by-catches every year [1,2]. Most of these events involve pinnipeds and cetaceans. One of the methods developed in recent decades to try to prevent cetaceans by-catches, particularly dolphins, is the use of acoustic repellents called 'pingers', that are set on fishing nets [3]. Pingers emit acoustic signals whose purpose is to repel dolphins from zones where fishing activities are taking place or to alert dolphins to the presence of fishing gear. These devices use relatively high-energy and high-frequency signals within the frequency range of dolphins' auditory sensitivity [4]. However, those signals are not directly related to dolphins' echolocation system nor their mode of communication.

This could partly explain why pingers' effectiveness is heterogeneous according to different factors such as species, fishing gears used or geographical zones [3,5]. The use of acoustic repellent devices for limiting dolphin by-catch during tests with professional fishermen showed positive results in some cases [6–8], but this method was not always effective [9]. Likewise, behavioural studies reported responses of dolphins to signals emitted by acoustic deterrent devices [10], while others found only subtle evidence [11] or even highlighted negative effects by decreasing echolocation activity and vocalisation time [12]. Notably, pingers can have some disadvantages. They can lead to habituation [13–15] as well as "dinner-bell" effects [7,16]. They may also have a negative impact on the dolphins' echolocation and communication by reducing the number of signals emitted [17], suggesting a reduced ability to detect a net and a higher probability of being caught [12,14,18]. Finally, if some repellent pingers are extensively deployed spatially (i.e., by numerous fishing vessels and/or set on long nets), they could create animal exclusion zones due to acoustic pollution, as hypothesised in several studies [8,19,20]. Therefore, the development of new and more effective acoustic devices without such undesired effects is necessary to limit dolphin by-catch [3].

Mortality due to accidental dolphin by-catch has been particularly critical in the Bay of Biscay, France, since 2016 [21]. By-catch mortality of the common dolphin *Delphinus delphis* (Linnaeus, 1758) was estimated as varying in yearly mean between 3973 (CI: 1998–6598) and 7800 (CI: 5200–12,760) individuals according to year and sources [22–25]. The population is estimated at 285,000 (CI: 174,000–481,000) individuals in the Bay of Biscay from January to April [26], for a total abundance of 467,673 individuals (CI: 281,129–777,998) in all the European waters of the northeastern Atlantic [27]. These levels of unintentional human-induced mortality are above the 1% threshold of additional mortality considered for the population to be sustainable [22,28,29], and have thus led to the failure to achieve Good Environmental Status for this species in the framework of the Marine Strategy Framework Directive [30]. This human-induced mortality rate is currently among the highest in the world for odontocetes. Worldwide, the highest known estimations of dolphin mortality are those for intentional captures of dolphins in Peru and Nigeria (respectively, 5000–15,000 and 10,000 catches every year [31]). In the Bay of Biscay, two fisheries composed of both French and foreign vessels are mainly involved: gill netters and pair trawlers [21,25]. After the PIC project in 2018 (acronym of "analysis of PIngers used for Cetaceans in fishing activities of pelagic trawlers and gill netters") [32], showing a mean reduction of dolphin by-catch by 65% (CI: 15–98%) with the STM DDD03L repellent pinger (from STM-products) installed on French pair trawlers, the device was made mandatory on this fleet composed of about 12 active pair trawlers in winter. However, yearly estimates of common dolphin by-catches from this fleet in 2004–2020 reached a maximum of more than 600 individuals caught (median value, with large between-year variations in estimates, ranging from less than a hundred in 2018 to more than one thousand in 2017) [33]. This highlights the responsibility of other fisheries such as gill netters with regard to dolphin by-catch [21,25]. Yet, encouraging the spread of STM DDD03L devices, or repellent pingers in general, over several kilometres of fishing gear, each deployed by more than 400 French gill netters, is not advisable for the reasons mentioned above relative to concerns about pingers. Although the exact causes of by-catches are still unknown, they might be due to the fact that dolphins do not detect fishing nets at the right time [34].

In this context, the project DOLPHINFREE ('Dolphins free from fishery by-catch') is working in partnership with SAS OCTECH Ocean Technology on the creation of a bio-inspired acoustic beacon, named CETASAVER-DOLPHINFREE, that emits a signal linked to the echolocation system of the dolphin to inform the animal of the presence of a fishing net. Dolphins use echolocation in combination with visual cues to investigate their surrounding environment [35]. First indications of the existence of an echolocation system in dolphins were observed for bottlenose dolphins in 1947, as these animals were able to avoid nets and find openings in enclosing nets at night and in murky waters, leading to the suspicion that dolphins used a biological sonar [36]. It should thus allow them to locate a fishing net at relatively short distances, between a few metres and a few tens of metres according to net reflectivity, angle of incidence, and source level of echolocation clicks [37,38]. Furthermore, playback experiments have shown that dolphins react to the echoes of their echolocation clicks as well as to computed echoes (i.e., "phantom echoes", generated from recorded echolocation clicks) [39,40]. For instance, dolphins were shown to be able to differentiate phantom echoes modified subtly by 3 dB or only 150 µs apart [41]. Moreover, a dolphin can accurately react to echoes of another conspecific echolocating on objects [42,43]. In addition, dolphins react when detecting a dead counterpart [44–46].

Based on this knowledge, the aim of the bio-inspired acoustic beacon prototype CETASAVER-DOLPHINFREE is to emit trains of returning echoes from echolocation clicks of a common dolphin performed on a fishing net to inform dolphins of the presence of a net. It thus uses informative signals in contrast with acoustic repellent devices. These echoes were obtained from a playback experiment involving echolocation clicks. The process of this experiment and the resulting signals remain confidential, the prototype CETASAVER-DOLPHINFREE being engineered and developed in partnership with the company SAS OCTECH. In short, the experiment consisted in playing a recording of a common dolphin's echolocation click, by emitting it on different types of fishing nets, with and without a dead dolphin (initially found stranded) entangled in the net, and then in recording the returning echo of the echolocation click. The aim of the bio-inspired beacon is to emit this signal of returning echo to inform dolphins of the presence of a net. The device is able to emit a complex signal within a high range of frequencies (20–200 kHz). The signal emission is omnidirectional by means of a dedicated ceramic and beacon conception, and the source level is 170–180 dB re 1 µPa at one metre. Two main different signals were created to be tested (i.e., echoes of fishing net, and echoes of a dead common dolphin embedded within a net) for three fishing nets (one nylon gill net and two different trawl nets; see details in Section 2.2). The purpose of the signals emitted by the bio-inspired device is to get the attention of dolphins when approaching a fishing net so that they will potentially identify its position by echolocating as well as communicating among individuals. To our knowledge, the concept of using such a bio-inspired acoustic beacon to limit dolphin by-catch mortality is new (see [47] to read about a beacon designed for porpoises developed using a different approach).

Thus, the aim of this work is to assess the behavioural response of wild common dolphins to signals emitted by a new generation of acoustic beacon, bio-inspired, as a mitigation device to limit fishery by-catch mortality. Since dolphins react to artificially emitted clicks (see above), we made the assumption that they would be able to detect and react to the acoustic emissions of the bio-inspired beacon. It could help dolphins to better detect fishing nets, which could ultimately enable them to avoid nets. To test this assumption, dolphins' behavioural patterns were studied by means of a sequential treatment (before/during/after being exposed to signals emitted by the bio-inspired beacon, with and without setting a fishing net). Visual observations and sound recordings of dolphins were assessed concurrently. Acoustic data collected required the use of automation methods to detect, identify and classify dolphins signals (i.e., echolocation clicks, buzz/burst-pulses, whistles). The main results of this work highlight an increase in the mean number of echolocation clicks and mean whistling time of dolphins by approximately 2.46 and 3.38, respectively, after activation of the beacon ($p < 0.01$). Visual surface observations showed attentive behaviours of dolphins, which kept a distance of a few metres to a few tens of metres away from the emission source before calmly leaving. Overall, these results suggest that common dolphins should have more chances to locate fishing nets and avoid them when the bio-inspired beacon is placed on a fishing net and activated.

2. Materials and Methods

2.1. Study Area

We conducted non-systematic scientific surveys to find wild dolphins, with opportunistic encounters, and to assess dolphins' behavioural responses to bio-inspired signals.

They were performed on 11–17 July 2020 and 9–18 July 2021 when weather conditions were favourable. It resulted in a total of 12 days at sea in the area of Pointe de Penmarc'h, Brittany, France (Figure 1), which is a location where strandings of dolphins occur [21]. The experiment and observations were carried out when the weather conditions were characterised by a wind approximately ≤ 10 knots and a swell of ≤ 1 m in order to be able to identify dolphins' behaviours. Experiments (i.e., observations, signal emission of the bio-inspired device, and audio recording of dolphins) were conducted from semi-rigid pneumatic boats 9.9 m (in 2020) and 6.5 m (in 2021) in length.

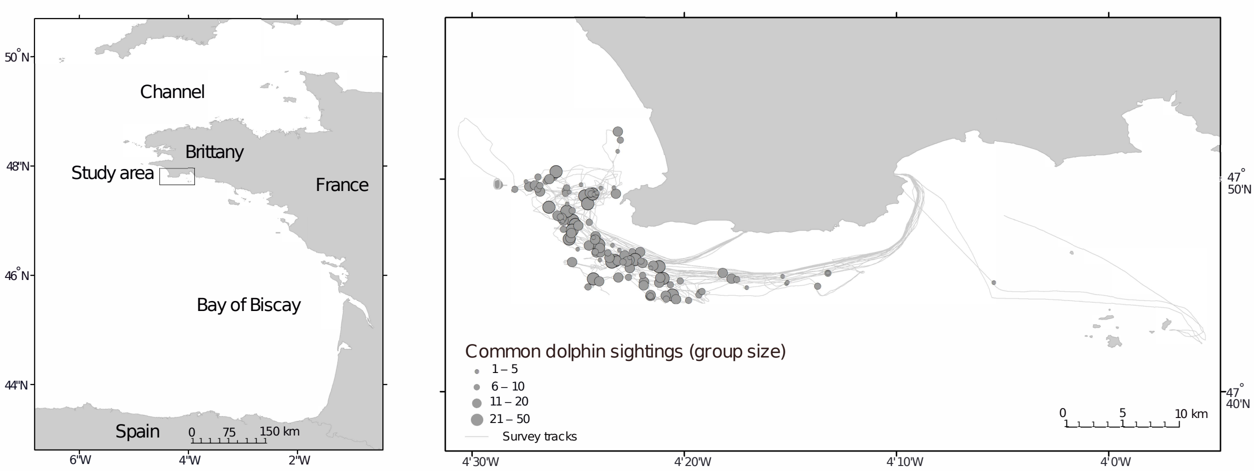

Figure 1. Map of dolphin encounters during the sampling campaigns.

2.2. Observations

As soon as a group of dolphins was observed, behavioural monitoring was initiated with a GPS (Global Positioning System) position read every minute on board. A group of dolphins was defined as any number of animals observed within five body lengths of any other dolphin, moving in the same direction and engaged in the same behavioural state [48–50]. The distance of each group of dolphins from the boat was initially estimated using rangefinder binoculars (Bushnell Fusion 10 × 42) to provide an accurate measurement of the distance and to allow observers to "calibrate" their visual estimation without binoculars. After each observer made several observations at the beginning of each survey (2020 and 2021), they switched to visual estimation without binoculars. Then, for the rest of the surveys, the distance was estimated visually, as it was a quicker and more pragmatic approach. When the group of dolphins showed a behaviour suited to the test requirements (i.e., a constant behavioural state for at least 1 min of observation), the experiment was initiated. The boat was stopped, the engine and sonar were switched off (the sonar being necessary to navigate in the study area, and operated at 190–210 kHz), and the beacon, placed at the end of a steerable boom, was positioned at a depth of 3 m on one side of the boat. The experiment was based on a sequential treatment with three sequences of observation of the dolphins' behaviours, which were initially planned to last five minutes each: before (BEF), during (DUR) and after (AFT) the emission signals from the beacon [12]. The BEF sequence is the control for the experiment; it enabled us to evaluate the behaviour of the dolphins when the beacon was switched off. The activation/deactivation of the emission was controlled with a switch from the surface. On the other side of the boat, at the same depth, was the hydrophone (see features below).

When a group of dolphins was detected, and then during the sequential treatment, behaviours of dolphins were noted on an observation grid [12,51]. The behavioural data from the visual observations were collected using the sampling method of Shane [48]. This method makes it possible to record different information at regular intervals. Firstly, information characterising the conditions in which the observation took place: weather conditions, time and GPS position of the dolphin group, group number, number of individuals, distance from the boat, percentage of dolphin group behavioural states (foraging, travelling, socialising, milling, attraction to the boat; defined in Table 1), setting an experimental fishing net (yes/no), I.D. of the signal emitted by the device, I.D. of the sequential treatment and nature of the treatment (BEF, DUR, AFT).

Table 1. Definitions of behavioural states of common dolphins recorded in 2020 and 2021 (according to [12,49,51]).

State	Definition
Foraging	Dolphins involved in any effort to pursue, capture and/or consume prey, as defined by observations of two or more of the following: fish chasing; erratic movements at the surface; multidirectional diving; coordinated deep diving; and rapid circle swimming. Prey often observed at the surface, as well as the presence of birds hunting.
Travelling	Dolphins engaged in persistent, directional movement making noticeable headway along a specific compass bearing. Group spacing varied and individuals swam with short (<20 s), relatively constant dive intervals.
Socialising	Animals were involved in active surface behaviour (frequent surfacing and breaching) that included physical interactions among group members and sometimes aerial behaviour.
Milling	Dolphins showed little movement, tended to remain in the same place and either spent floating at the surface or surfaced asynchronously.
Attraction	Dolphins came towards the boat and swam at a few metres along it, following its direction.

In addition, response variables (4 qualitative, 1 quantitative and 1 semi-quantitative) for the behavioural study were filled in (see details in Table 2): the structure of the group (dispersed or compact), the direction it followed (variable or constant), the diving time (variable, short or long), the speed of movement (slow or fast), the percentage of different behavioural categories categories of behavioural events (dolphins of the group surfacing simultaneously, active swimming on the surface, diving, jumping) [12,51] as well as the intensity of the response to the signal emitted by the beacon (0, 1 or 2). The distances 5–30 m of dolphins from the boat used for these response modalities (see Table 2), even if rough, were partly defined from estimated distances corresponding to the detection of a net by a bottlenose dolphin using its echolocation system [38] also considering that beyond 30 m, behaviour can no longer be precisely observed and that dolphins moved away once they had investigated the signal emitted by the device and the surrounding situation. Surface behaviours of dolphins were assessed by observers on the boat.

To assess dolphin behavioural response to different fishing nets used by professional fishermen, the experiments were carried out with and without setting one of the four following nets (two gill nets and two different trawl nets): (i) monkfish gillnet, nylon, mesh 220 mm, (ii) trawl net, mesh 12 mm, thread 210/24/413, reinforced nylon, (iii) trawl net, mesh 40 mm, thread 4 mm, polyethylene PE, (iv) hake and pollack gillnet, stretched mesh 136 mm (non-standard), tread 0.6 mm, with a weighted 12 mm-diameter bottom rope. Nets were set at the edge of the boat on the same side where the beacon was positioned at 3 m depth. Nets (i) to (iii) used in 2020 were placed between 2 and 4 m depth (net height 2 m, length 4 m) and, due to the time and handling necessary to set net (iv) used in 2021 (20 m long), it was set from the surface to 3 m deep. Overall, experiments were mainly conducted with nets (i) to (iii). The effect of each fishing net, or the absence of fishing net, on the behaviour of dolphins was recorded without the emission of signals from the beacon during BEF sequences.

Table 2. Nature and definitions of the behavioural response variables of common dolphins recorded in 2020 and 2021.

Variable Name	Nature	Definition	References
Structure of the group	Qualitative	'Compact' if <5 body lengths between all individuals of a group or 'Dispersed' otherwise.	Adapted from [49]
Direction followed	Qualitative	'Variable' or 'Constant'.	-
Diving time	Qualitative	'Short' if <1 min, 'Long' if >1 min, or 'Variable'.	Threshold adapted from [52]
Speed of movement	Qualitative	'Slow' if <10 km/h or 'Fast' if >10 km/h. 10 km/h being the travelling speed of common dolphins.	Travelling speed from [53]
Behavioural events	Quantitative	Dolphins of the group surfacing simultaneously, doing active swimming on the surface, diving, jumping. Estimated using percentage.	[12,51]
Intensity of response	Semi-Quantitative	When the beacon emitted: '0': no change in behaviour, '1': attentive behaviour to the signal without moving 5 m away from the emission source, '2': attentive behaviour to the signal and moves at least 5–30 m away from the emission source. Attentive behaviour means that the dolphins oriented themselves towards the emission source and were prospecting, doing back and forth movements in parallel with the emission source/boat, before calmly leaving.	Threshold adapted from click detection range [38]

Acoustic data were collected using an Ocean Sonics icListen HF hydrophone (dynamic range: 118 dB, sensitivity: −170 dBV re. µPa). Recordings were made on one channel with a sampling rate of 512,000 Hz which allowed the study of frequencies up to 256,000 Hz (Nyquist–Shannon Theorem). The audio bit-depth is 32-bits. Together, these parameters allow for a precise sampling of common dolphin signals in the vicinity. The hydrophone was set up to create a .wav file every minute (each file being 90 Mb). A total of 361 recordings of one minute were considered. Audio data cleaning was performed using the Audacity software v.2.0.5.0. and v. 3.1.1.

In addition to modalities BEF, DUR and AFT of the explanatory variable of the sequential treatment, modalities BEF + DUR and DUR + AFT modalities were also considered (Table 3). They correspond to the activation and deactivation, respectively, of the beacon during a one-minute recording. It was decided to keep these records (i.e., not cutting and attributing them to separated modalities) as they represent important events: they show the transition from silence to the emission of signals by the bio-inspired beacon, and conversely. These two additional modalities were used to investigate a potential change in the behaviour of the dolphins during the transitions of the sequential treatment.

Table 3. Number of acoustic recordings per modality of treatment. Each recording lasts one minute. BEF: Before activation of the beacon, DUR: During activation, AFT: After activation.

Fishing Net	Treatment Sequence					Total Sequences
	BEF	BEF + DUR	DUR	DUR + AFT	AFT	
Present	12	26	103	27	39	207
Absent	26	26	73	18	11	154
Total sequences	38	52	176	45	50	361

2.3. Data Extraction

Dolphins emit four main types of acoustic signals, which are each associated with a specific use: (i) echolocation clicks: clicks of high energy on a wide frequency range, used to detect objects/situations in their environment and get a sense of their surroundings [54]; (ii) burst-pulse: series of clicks with inter-click interval (ICI) $<$ 10 ms [55]; (iii) buzz: series of clicks with ICI $<$ 10 ms, preceded by a slower train of clicks [55]; (iv) whistles: relatively low-frequency vocalisations, mainly used for intraspecific communication [35].

Buzz and burst-pulses (or grouped as "BBP") are used by dolphins in different contexts [56]. The use of BBP has been documented in social communication for some delphinid species in replacement of or in addition to whistles [57,58]. Moreover, buzzes allow for high rate feedback during prey hunting [59], while burst-pulses are used more often in social interactions [60–62]. However, they remain close in their structure (i.e., a series of fast clicks differentiated by the acoustic activity preceding them, such as whistles or accelerating rate of echolocation clicks) and thus difficult to differentiate. To assess the acoustic activity of dolphins (i.e., whistles + echolocation clicks + BBP), the detection and identification of each of these types of signals is needed. In the following part, the methods used to automatise these detections are presented. Algorithms were coded in Python 3.9.7 [63] and are provided with processed data needed to reproduce the results presented in this article (see Data Availability Statement).

2.3.1. Detection and Identification of Echolocation Click, Buzz and Burst-Pulse

To identify click-like signals in recordings, a detector adapted to our dataset was created from an approach used in previous works on marine mammals, mainly sperm whales [64,65]. Structurally, a click is a high-energy event of very short duration (usually less than 0.5 ms). To detect them, a high-pass filter (freq $>$ 50 kHz) was first applied to our raw recordings (Figure 2). This prevented whistles and other low-frequency sounds from affecting the detection. Then, the Teager–Kaiser operator [66] was applied, which allowed us to estimate the energy contained in an acoustic system, improving the signal-to-noise ratio. Finally, local maxima were selected in the filtered signal (see Figure 2) as they correspond to high-energy events, i.e., clicks.

Our aim was to detect 2 types of clicks: echolocation clicks and BBP (two paths in Figure 2). Their main differences are: (i) their ICI: less than 10 ms for BBP [55] and (ii) their amplitude, which is lower for BBP by about 10–20 dB [55,56]. As a result, we set two different thresholds of energy (no unit) to extract local maxima from the signal's energies: 1×10^{-3} for echolocation clicks and 1×10^{-5} for BBPs. These two different selections were performed separately.

Once the echolocation clicks were identified and selected, we needed to exclude all signals emitted by the acoustic beacon, which, in their construction, closely resembled returning echoes from echolocation clicks emitted by actual dolphins. The beacon emits trains of 10 signals 0.101 ± 0.001 s apart. Knowing that dolphins do not usually emit echolocation clicks with such regularity, we identified and excluded all click-like signals which were 0.101 s apart in the recordings in order to differentiate signals emitted by the beacon from dolphin clicks (Figure 2). This method enabled us to keep only clicks emitted by dolphins in the last step of our selection (Figure 3a). In addition, to exclude all possible noise (such as the sonar of the boat sometimes left on unintentionally), the remaining clicks were projected in a 2D space according to three extracted features: mean frequency, median frequency and standard deviation, using a Uniform Manifold Approximation and Projection for Dimension Reduction (UMAP [67]) as a method of unsupervised classification (see Appendix A). This enabled us to group and identify falsely detected echolocation clicks (i.e., sonar's signals emitted from boats). We also checked that the sonar left on unintentionally, in 15.5% of the recordings, had no impact on the detected acoustic activities of the dolphins (see Figure S1). Finally, 195,153 dolphin echolocation clicks were kept from the initial selection.

Regarding BBPs, the approach used for their detection and identification is rather different (see Figure 2). The threshold of energy for click detection was lowered to 1×10^{-5} in order to detect BBPs clicks. However, this also led to the detection of echoes from various sources in the surrounding environment. Such echoes are usually less than 10 ms apart, which makes them likely to be detected as BBPs (see previous (i)) if no additional criteria are considered (see Figure 2). Furthermore, the bio-inspired beacon emits signals of high energy, which produce echoes that could be mistaken for a BBP. To counter this difficulty, we used a semi-automatic method to detect and identify BBPs. First, we selected potential BBPs candidates automatically using the following empirically identified conditions (summarised in Figure 2): (i) ICI < 20 ms on a series of more than 15 clicks, (ii) mean energy (amplitude of the signal after Teager–Kaiser operator) of a series < 0.1, (iii) difference of amplitude between two successive clicks < 0.1, (iv) exclusion of relatively short series with clicks of decreasing energies (regression slope < -0.5). Then, we manually reviewed each detection and labelled each one as a 'Buzz', a 'Burst-pulse' or an 'Error' according to descriptions from other studies [55,56]. Criteria chosen for the automatic detection were intentionally imprecise so that no BBP could be missed. The drawback of this choice was the detection of many false positives, which were easily recognisable manually with an observation of the frequencies of each click.

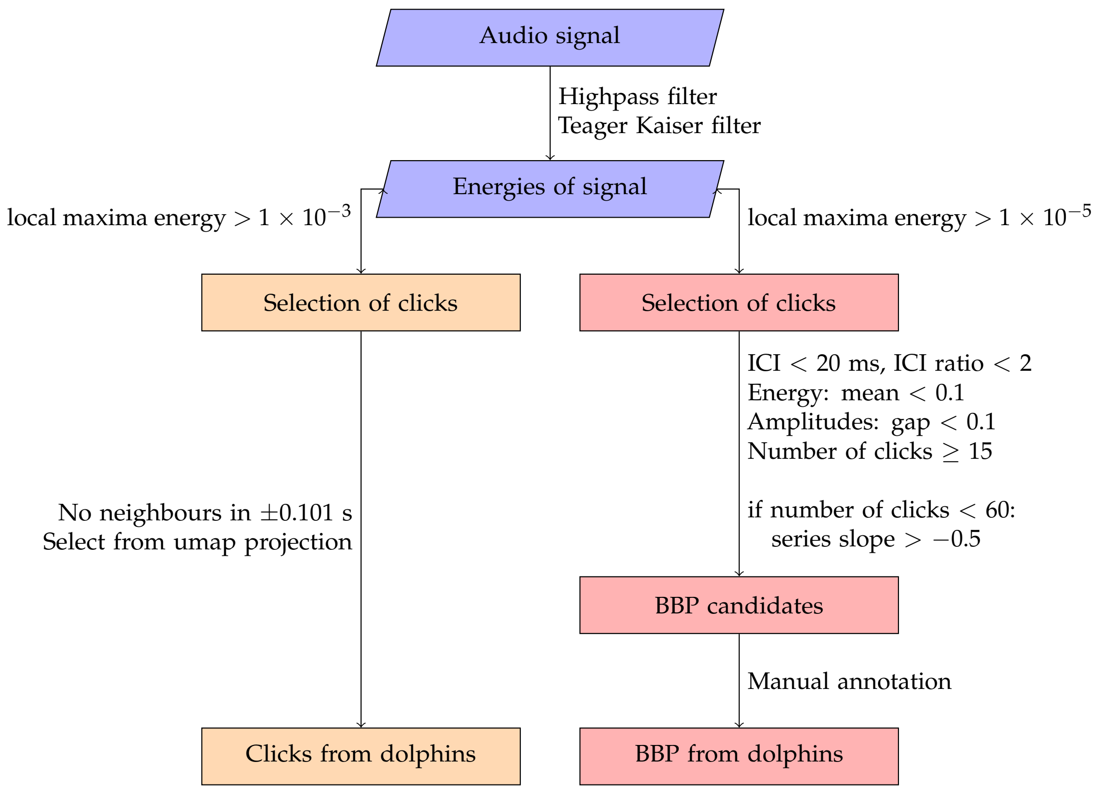

Figure 2. Diagram of the algorithm used to detect echolocation clicks (yellow path) and buzzes/burst-pulses (BBP, red path) in audio recordings.

The use of semi-automatic detection was mandatory due to the presence of echoes coming from signals of the bio-inspired beacon rebounding in the environment. By removing the step of manual annotation, the method is quite similar to that used for the selection of echolocation clicks (see Figure 3). In total, this process enabled us to identify 570 buzzes and 231 burst-pulses in the recordings. This distinction between pulsed sounds is not widespread in the scientific literature on common dolphins. Since we are interested in the overall acoustic activity for these kinds of signals, burst-pulse and buzzes were ultimately analysed together (similarly to [68]), but separated analyses are available in Appendix B.

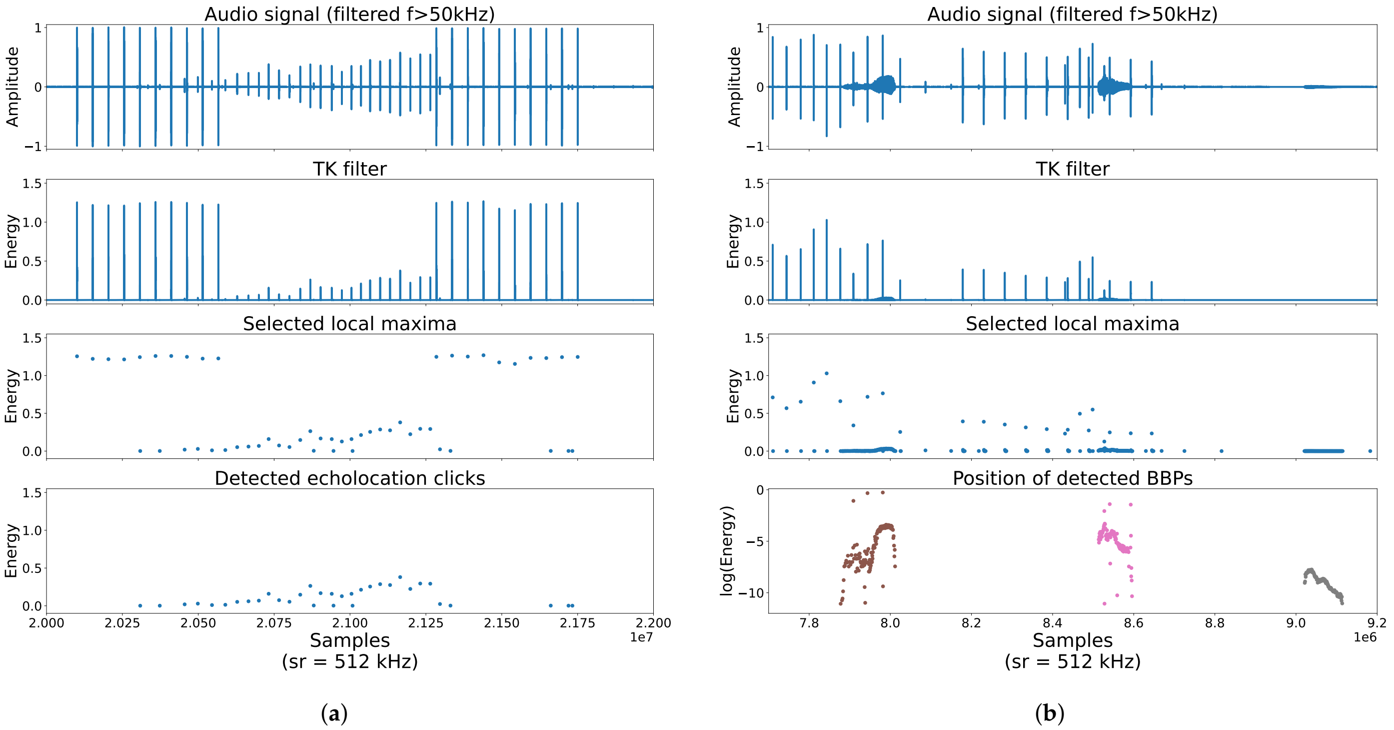

Figure 3. Comparison between the main steps in the selection process of echolocation clicks and buzzes/burst-pulses (BBP). Vertical lines with amplitude ≈ 1 in (**a**) are signals emitted by the prototype of a bio-inspired beacon. (**a**) Main steps in the selection of echolocation clicks from a recording of 11 July 2020 at 12:35 p.m. (**b**) Main steps in the selection of BBP from a recording of 11 July 2020 at 9:04 a.m. Different colours show distinct BBP series.

2.3.2. Vocalisation Detection

Whistles appear as lines of high energy in the lower frequencies. Selecting by hand all the whistles from 361 min of acoustic recording would be long, laborious and error-prone. Thus, to detect and identify whistles, a vocalisation tracking method is necessary. Selecting vocalisations in an audio track is a complex task, and several techniques have already been developed to achieve it: statistical modelling of whistles [69–74], tracking algorithms based on hand-picked parameters [75–77], image processing approaches [78–83] or deep learning models associated with clustering methods [84,85]. For our dataset, we chose to adapt a tracking algorithm developed during the DECAV project [86]. The original code written in Matlab was optimised and transcribed in Python for the needs of this study. The steps of this algorithm are described in Figure 4.

Compared to the original algorithm [86], only the "removal of harmonics" step was added. The original algorithm selected all vocalisations and labelled them each as different trajectories. Therefore, harmonics—which are a repetition of the same trajectory at higher frequencies than the fundamental one—were considered as new vocalisations whilst they are not. This step checked for overlapping sections in selected trajectories and then made a regression among them. If the R^2 of this regression was >0.5, then only the trajectory with the lowest frequency (the fundamental) was kept. In addition, the threshold for energy detection was decreased from 10 to 6 times the geometric mean [86] to extract more whistles. Strict continuity criteria of 2.7 ms and 187 Hz [86] were used to avoid errors. These criteria control the maximum distance (in time and frequency) between two fragments of detected whistles to consider that they are part of the same entity. Finally, a "sparsity" parameter was added, indicating the proportion of missing pixels in a trajectory. If sparsity > 0.5, then we considered the trajectory to be too imprecise, and it was excluded from the selection.

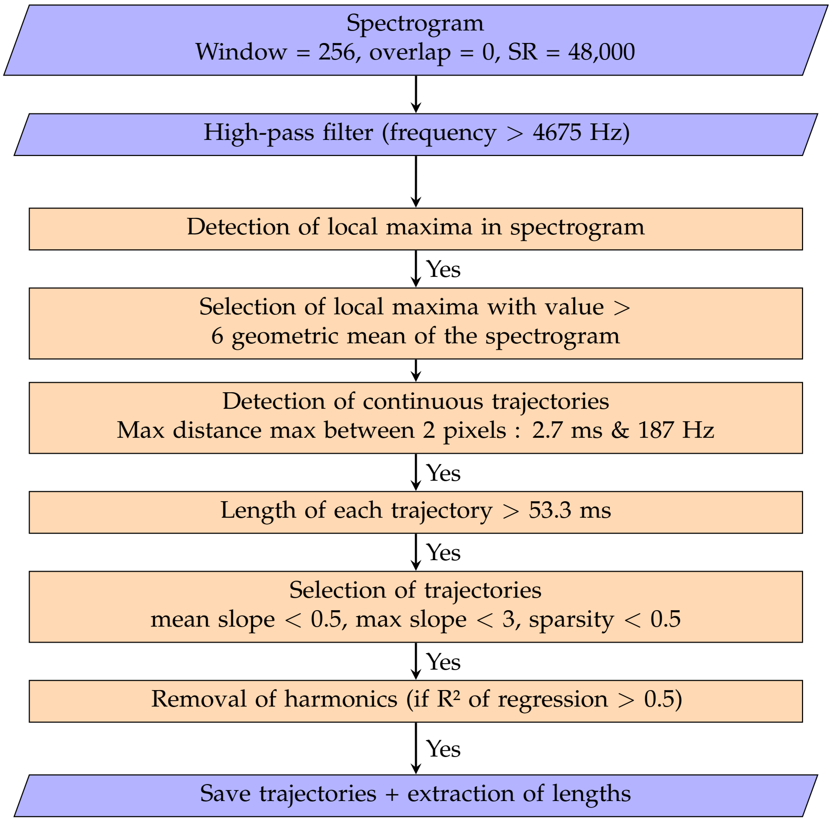

Figure 4. Steps of the algorithm used to detect dolphin whistles in audio recordings. Adapted from the DECAV report [86]. SR: sampling rate.

Tracking results for two extracts can be observed in Figure 5. In the case of isolated whistles (Figure 5a), the algorithm could succeed in locating the beginning and the end of each vocalisation. On the other hand, as soon as the signal becomes more complex with overlapping whistles and trajectories that intersect, the algorithm is less likely to select each whistle as a unique entity but more as several fragments (Figure 5b). The algorithm is thus able to detect whistles but not identify them. Improving the identification of distinct whistles would demand the development of a specific algorithm, which would assign each trajectory to a different whistle. For this reason, the number of whistles detected was not used to assess the whistling activities of dolphins. Instead, the duration of the whistles detected in a one-minute recording were added together and divided by the number of dolphins present during that time. Thus, the whistling activity is assessed by using the mean whistling time per audio per dolphin. Time spent whistling has also been studied in the frame of experiments concerning the behavioural response of dolphins to a pinger [12].

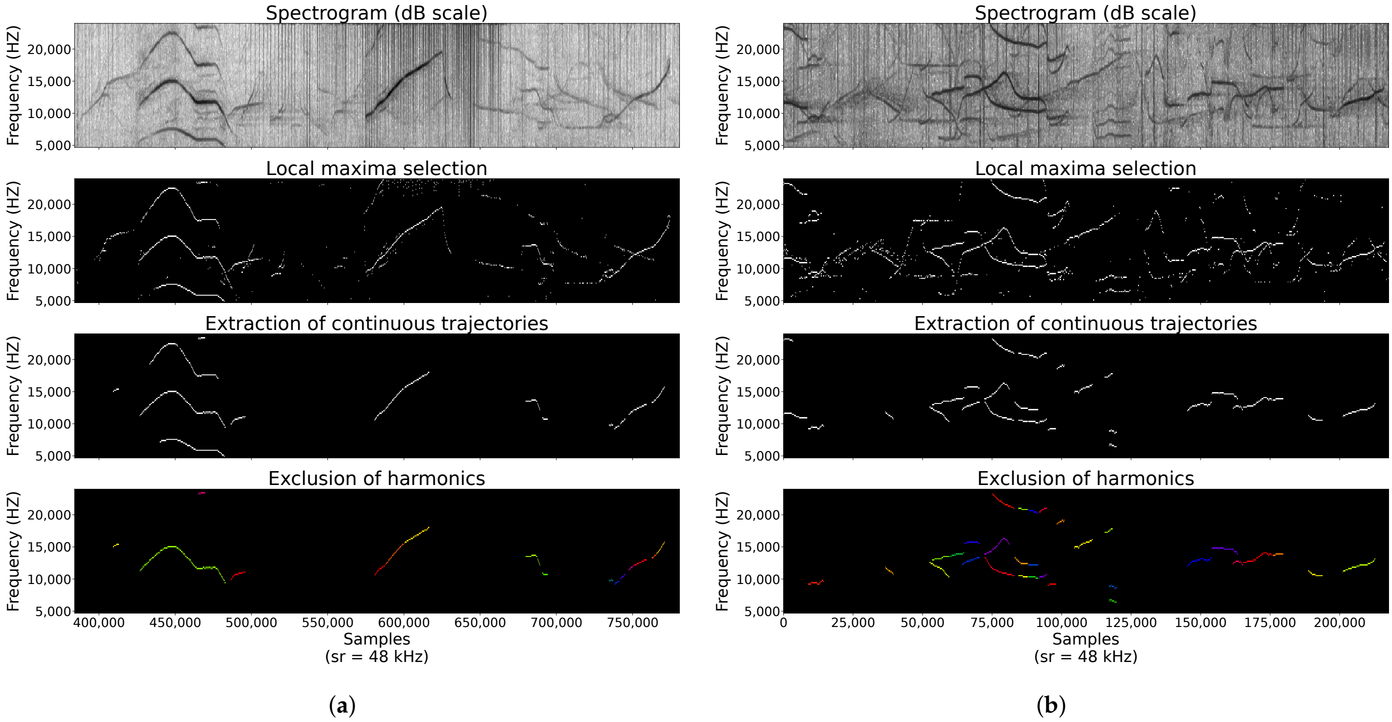

Figure 5. Steps of the method used to extract whistles from spectograms in two cases: isolated whistles (**a**) and overlapping whistles (**b**), using strict continuity criteria. Different colours show fragments identifed as different whistles. SR: sampling rate. (**a**) Main steps in the extraction of whistles from a recording of 12 July 2020 at 9:40 a.m. (**b**) Main steps in the extraction of whistles from a recording of 13 July 2020 at 7:39 a.m.

2.4. Data Analysis

Firstly, regarding behavioural data from visual monitoring on the boat, nine response variables were considered (see Section 2.2): four quantitative and five qualitative. The assessment of the effects of the signals emitted by the beacon was performed by comparing the values among treatment sequences with (i) for quantitative data, box plots (distribution of the values of each variable between the sequences), Friedman's non-parametric statistical test implemented for each variable, a permutational multivariate ANOVA (PERMANOVA [87]) on the matrix of Euclidean distances computed among the observations for all variables, and a Principal Component Analysis (PCA [88]); (ii) for qualitative variables, the Chi-squared (or Chi2) test of independence on the contingency table crossing the numbers obtained for each of the modalities of a response variable with those of the treatment variable, and a Multiple Factor Analysis (MFA [89]) if the null hypothesis H0 of independence among variables was rejected by the Chi-squared test.

Secondly, detected acoustic activities (i.e., time spent whistling, echolocation click and BBP counts) were collected for each one-minute recording according to two explanatory variables: (i) presence of fishing net (i.e., presence/absence) and (ii) the sequential treatment (i.e., before, during and after activation of the acoustic beacon) (Table 3). We also considered the predominant behaviour of the group (i.e., the group behavioural state which represented more than 50% of the behaviour of the animals during observations, adapted from [49]) observed during recording for each group of dolphins: foraging, travelling, socialising, milling or attraction to the boat (see definitions in Table 1) as in previous studies [12,49,51]. The effects of the type of fishing net used and the type of signal emitted by the prototype were not integrated in our statistical models as several modalities contained too few samples and were overall too unbalanced. In such cases, existing methods to try addressing unbalanced sampling (such as undersampling, oversampling, data cleaning, or hydrid approaches, e.g., [90]), would lead to too many errors in data estimation to use them accurately. Thus, patterns were investigated graphically by means of values distribution (mean and confidence interval, see Supplementary Material Online). The effect of the observed number of dolphins per group was considered as an offset for count data in models below.

It was hypothesised that counts of acoustic activities were dependent on group size (as other studies assumed [55,91]). Therefore, there were divided by the number of dolphins per group, and the result often followed a distribution of quasi-Poisson. For rare events, such as BBPs or whistles, data were zero-inflated. Thus, we used two types of models to test differences in acoustic activities among experimental modalities: negative binomial Generalised Linear Model (NB GLM, [89]) for echolocation clicks, and zero-inflated negative binomial regression model (ZINB, [92]) for BBPs and whistles. We checked for model assumptions on residuals after fitting. In those models, the null hypothesis (H0) was that all mean values are equal among treatment modalities. The alternative hypothesis (H1) was that at least one mean value was different from at least one other mean value. When H0 was rejected, a Tukey adjusted post hoc test was computed to assess more precisely which mean values were equal/different among treatment modalities. All statistical analyses were performed with the R programming language in R studio [93,94].

3. Results

84 groups of common dolphins were observed in the surveyed area during the 12 days at sea. The size of each group varied between 1 and 40 individuals, with an average of 10 $\pm$ 7 individuals (standard deviation), and with a median of 8 individuals. A total of 83 observation sequences were carried out, including 59 where beacon emission was performed with 47 different dolphin groups. Among the 83 observation sequences, 258 observation lines were completed with 186 associated with a sequential treatment of the beacon experiment: 78 BEF, 83 DUR, and 25 AFT. Several sequential treatments with beacon emission were performed almost successively with the same group (this was completed for nine groups, between two and four sequences with emission according to the group, for a total of 26 sequences). The relatively lower number of AFT observations illustrates that shortly after the beacon was emitted, the groups of dolphins moved away to a distance at which it was no longer possible to make precise observations.

3.1. Surface Visual Observations

First, we investigated response variables that roughly assessed the dolphins' behaviour: (i) a quantitative variable (i.e., percentages of four categories: dolphins in the group surfacing simultaneously, active surface swimming, diving, jumping), and (ii) four qualitative variables (i.e., group structure (dispersed or compact), direction followed (variable or constant), diving time (variable, short or long), speed of movement (slow or fast)). No changes were underlined for these two types of variables, defining rough behaviours, among the three treatments BEF, DUR, and AFT (Friedman's test, $p > 0.05$; Chi-squared tests of independence $p > 0.05$, respectively).

Secondly, concerning more specifically the 83 visual observations made during the DUR sequence (i.e., beacon emission), there was a relationship between response intensity and the signal emitted (Chi-squared test of independence, Chi2 = 58.20, df = 18, $p < 0.001$) but not between response intensity and the presence/absence of the net set into the water (Chi-squared test of independence, Chi2 = 3.60, df = 2, $p > 0.05$). The response intensities of the dolphins were the following (Figure 6, Table S2): intensity 0 = 7 observations, intensity 1 = 17 observations, intensity 2 = 47 observations, and NA = 6 observations without intensity mentioned in the observation grid during the survey. Six additional observations were not considered for analysis because the related sequences were cancelled (beacon activated too late). Response intensities 1 and 2 cumulatively represented 83.12% of the observations (Figure 6).

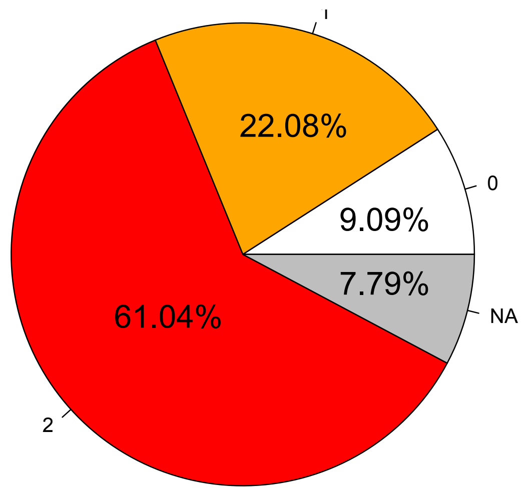

Figure 6. Percentage of response intensity (0, 1, 2; see Section 2.2 for details) of dolphin groups to signals emitted by the bio-inspired beacon. NA: observations without intensity noted during the survey.

3.2. Acoustic Behaviours of Dolphins

The acoustic activity of dolphins changed when the beacon emitted. Firstly, the mean numbers of echolocation clicks and of BBPs varied among experimental treatment sequences (NB GLM, Chi2 = 26.9, df = 4, $p < 0.001$, and ZINB, Chi2 = 10.6, df = 4, $p < 0.05$, respectively). In particular, echolocation clicks and BBPs followed a common trend (Figure 7d, e): the mean number of signals increased at beacon triggering (BEF+DUR), decreased slightly during emission sequence (DUR) but remained higher than in any other experimental sequences, and then decreased at beacon deactivation (DUR+AFT and AFT). More specifically, among BEF and BEF+DUR, the mean number of echolocation clicks per dolphin increased by 2.46 times (from 43.8 to 108; Figure 7d, Tukey post-hoc, $p < 0.05$), and the mean number of BBPs increased by 3.46 times (from 0.132 to 0.457, with high variability; see Figure 7e, $p > 0.05$), i.e., almost tripling the activity for both click-type signals.

Secondly, whistling time per dolphin also showed differences in mean values according to experimental treatment sequences (ZINB, Chi2 = 18.9, df = 4, $p < 0.001$). The mean whistling time per dolphin increased by 3.38 times between BEF and DUR sequences, from 0.178 to 0.602 s (Tukey post hoc, $p < 0.01$). The mean time spent whistling stayed high during the whole activation, only decreasing after the beacon was turned off (Figure 7c). However, whistling time per dolphin in the DUR+AFT sequence varied strongly (Figure 7c), whereas a decrease was observed for echolocation clicks and BBP numbers (Figure 7a–c).

When considering separately the acoustic activity recorded during treatment sequences with or without setting a fishing net (Figure 7d–f), overall, the trends among sequences were similar to those described above (Figure 7a–c). Interestingly, during treatment sequences, there was almost always less acoustic activity when there was no fishing net set underwater. Data of all sequences gathered together highlighted that the presence/absence of a fishing net underwater had an effect on the mean values for all communication types ($p < 0.05$ for the three models, see Figure S2). Moreover, mean values of acoustic activities are mostly higher at each modality of treatment sequence when a fishing net is present (Figure 7d–f), but without statistical differences ($p > 0.05$) due to high variability. In Figure 7b, e, the difference in confidence intervals between BEF+DUR and other treatment sequences is due to some recordings containing many more BBPs for this sequence (with a maximum of 10 BBPs per dolphin per recording).

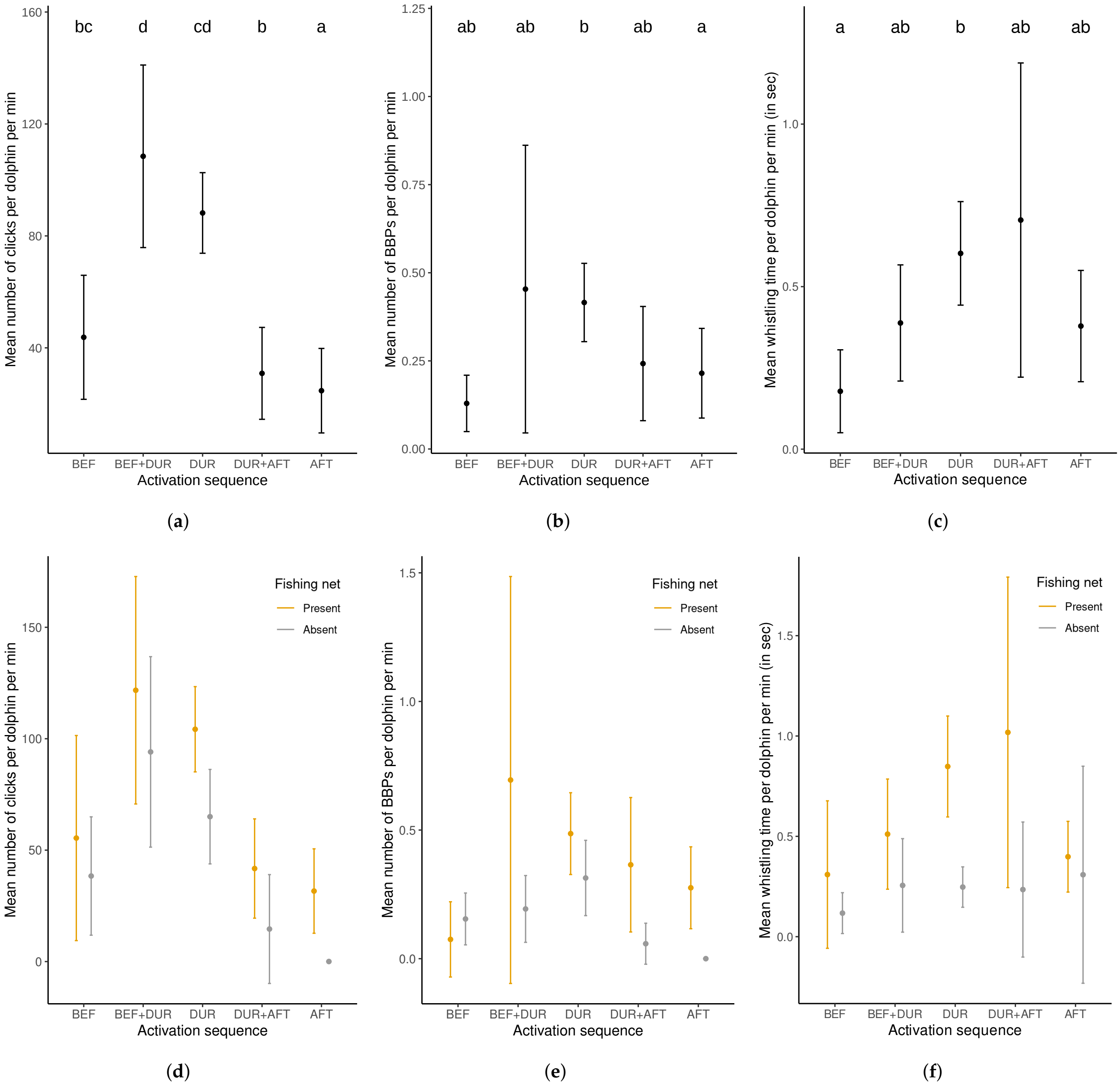

Figure 7. Detected acoustic responses of dolphins during sequential treatment, for each type of dolphin signal emitted (columns), according to the presence/absence of fishing nets (**d**–**f**), and aggregated (**a**–**c**). Modalities with different letters mentioned above upper confidence interval bars have different mean values (H0 rejected by Tukey's post hoc test), only shown for (**a**–**c**). Ranges show 95% confidence intervals. BEF: Before activation of the beacon, DUR: During activation, AFT: After activation. (**a**) Detected echolocation clicks during each treatment sequence. (**b**) Detected BBPs during each treatment sequence. (**c**) Identified whistling time during each treatment sequence. (**d**) Detected echolocation clicks during each treatment sequence, with and without net. (**e**) Detected BBPs during each treatment sequence, with and without net. (**f**) Identified whistling time during each treatment sequence, with and without net.

In addition, when analysed separately, it should be noted that the mean number of buzzes and burst-pulses varied according to the absence/presence of a fishing net set underwater (Figure S2, pairwise Tukey test, $p < 0.001$). The mean number of burst-pulses also varied among sequential treatments (ZINB, Chi2 = 10.3, df = 4, $p < 0.05$). With regard to buzzes, while we could also observe a similar trend as burst-pulses, there were no statistical differences among modalities (ZINB, Chi2 = 4.9, df = 4, $p > 0.05$). Meanwhile, differences in mean numbers of BBPs were mainly explained by the behaviour of dolphins during recordings (i.e., foraging, travelling, socialising; see Appendix B for more details). In contrast, the behaviour had no effect on the mean number of echolocation clicks emitted nor on the mean time spent whistling (not shown).

Moreover, differences existed in the acoustic activity of dolphins among fishing net types set during experiments (Figure S3, Kruskal–Wallis test, Chi2 values were 47.8, 15.2 and 30.2 for clicks, BBPs and whistles, respectively; with df = 4 and $p < 0.01$ each), which was higher when the gill net was set (Figure S3). Overall, the acoustic activity was lower during control sequences (i.e., when no fishing net was set). Each fishing net was associated with corresponding signals (i.e., a fishing net with or without a dead dolphin caught) emitted from the beacon (see Table S1 for details), for which some differences were also observed on the dolphins' acoustic activity (Figure S4, Kruskal–Wallis test, Chi2 values were 69.5, 48.8 and 101.1 for clicks, BBPs and whistles, respectively; with df = 10 and $p < 0.01$ each).

4. Discussion

The goal of the bio-inspired acoustic beacon is to inform common dolphins of the presence of fishing nets in order to limit by-catch. The device emits signals corresponding to trains of echoes coming from echolocation clicks performed on a fishing net or on a fishing net containing a dead common dolphin. Results showed that the acoustic activity of common dolphins (i.e., echolocation clicks, BBP, whistles) increased when the beacon was activated. In addition, visual surface observations showed attentive behaviours of dolphins, which kept a distance of a few metres to a few tens of metres away from the emission source before calmly leaving.

Firstly, the mean number of echolocation clicks was multiplied by 2.46 at beacon activation. This highlights that dolphins echolocate much more when the informative signals are emitted from the device. Two interpretations could be put forward to try to explain this response: dolphins could interpret the signal sent by the beacon and echolocate by themselves to locate a fishing net they had not been aware of before, or dolphins struggle to understand the signal sent by the beacon, so they echolocate to clear up ambiguities. Either way, it means that dolphins tried to be more aware of their surrounding environment. Secondly, the mean time spent whistling increased by a factor of 3.38 at beacon activation. Likewise, the mean number of BBPs increased despite showing no statistically significant differences due to high variability at the BEF+DUR sequence. BBPs and whistles are signals that can be used by dolphins to communicate among individuals. The increase in mean BBP numbers and in time spent whistling upon beacon activation suggests that dolphins communicate differently and more, potentially favouring awareness among them. Moreover, whistling time only started to decrease during the AFT sequence, while it is sooner for BBPs and echolocation clicks. This might be due to the fact that dolphins first reacted to the beacon by echolocating to investigate their surroundings, producing BBPs and whistling to communicate and then continuing to communicate by whistling. This also suggests that whistle types could be different among DUR and AFT sequences once dolphins had prospected and identified the situation. Investigating such differences about whistle types will need complementary analyses (see below).

Previous studies dedicated to repellent pingers showed that some of these devices can induce a reduction in echolocation rates [10,12,13] and vocalising time [12] on dolphin species and other marine mammals [14]. This response could increase the likelihood of entanglement as suggested by these studies. In contrast, the bio-inspired beacon induces an increase in the mean numbers of clicking and whistling time of common dolphins, which may increase the likelihood of detection of the fishing net. Moreover, the number of echolocation clicks that we detected may be slightly underestimated due to the fact that by chance, some clicks emitted by dolphins could have been exactly 0.101 s apart (i.e., signal interval within trains emitted by the device) and therefore excluded from the selection (see Section 2.3.1).

Dolphins' responses could be further studied by investigating differences in whistle types (i.e., in terms of shapes and/or frequencies) and rates, which could possibly indicate a change in dolphin behaviours [68,91,95]. This would involve an accurate identification of each whistle. However, this task is complex, and detection techniques developed so far have not been able to solve this problem without errors [69–82,84,85]. If whistles are first identified, then a classification of whistles using unsupervised classification techniques such as UMAP [67] could be applied, also using a metric to determine the optimal number of clusters [95]. The classification of signals emitted by dolphins is also possible with an auto-encoder in Deep Learning [96]. However, both approaches require building a training data set by a time-consuming manual annotation of each whistle, which was not performed on our data that included about 7800 whistles.

With regard to BBP, different buzzes can be associated with various social, foraging or feeding behaviours of dolphins [97]. Buzzes are often used to catch prey [55], which is supported by our results: buzzes are emitted mainly during foraging. However, it has been shown that buzzes can also be used as "emotional" signals whether in a positive situation, e.g., when getting a prey [58,98], or during a situation of aggression among dolphins [62]. Burst-pulses play a role in social behaviours [60,61], which corroborates to our recordings where they were mostly observed during socialising (Figure A2). They might be used to broadcast emotions to other dolphins [99]. Finally, annotations produced in this study could be used to train a Machine Learning algorithm [100] to remove the need for human intervention in the semi-automatic process of BBP selection.

Although it was not always observed [9,19], some repellent pingers can induce aversive behaviour in marine mammals [17,101] or even a stressful escape behaviour, which was notably observed on a group of common dolphins with the STM DDD03L repellent pinger [51], which has been mandatory since 2019 for French pair trawlers in the Bay of Biscay. In contrast, using the bio-inspired prototype, visual surface observations showed attentive behaviours of dolphins, which kept a distance of a few metres to a few tens metres away from the emission source before calmly leaving without showing any signs of "fear" reactions, which corresponds to estimated net detection distances of (bottlenose) dolphins [38]. Interestingly, the acoustic activities of dolphins varied according to the type of fishing net set up underwater; it was the highest when a nylon gill net (i in Section 2.2) was used (Figure S3) and the lowest when the long nylon gill net was used (iv in Section 2.2). Control sequences with no fishing net showed reduced levels of acoustic activity, but they remained higher than when the long gill net was used. However, only eight recordings of signals of dolphins could be obtained when this fishing net was set up, which makes it difficult to compare it with the other types of fishing nets.

Together, our results show that bio-inspired signals emitted by a beacon device have an effect on the behaviour of dolphins by increasing their acoustic activity. Moreover, it increases when the beacon was emitting—both when a fishing net was present in the water and when it was absent. This shows that the dolphins reacted to the signals emitted by the beacon even in the absence of a fishing net, as observed in other studies [39–41]. In addition, the increase in acoustic activity when the beacon was emitted was greater in the presence of a submerged fishing net. It should be noted that the experiments were carried out during daylight hours but with very low underwater visibility (about <3 metres). Dolphins were therefore more likely to use acoustic detections than visual aids, as confirmed by surface visual observations made during experiments where behavioural responses of dolphins could be observed at a distance greater than 3 m from the boat. These results suggest that the bio-inspired beacon led common dolphins to increase their echolocation activity and communication, which in turn should favour net detection and thus may reduce the chances of by-catch without visible stressful escape behaviour observed with some repellent devices [51].

During the experiments, no behavioural attraction was observed when the beacon was activated. Habituation to signals [3,13,14,101] could not be tested, as it was difficult to reproduce the experiments within the same groups of dolphins. The sequence could be repeated two to four times (according to the group) on nine groups for a total of 26 sequences. These sequences could be considered as pseudo-replicates within each dolphin group, but we included them in the same analyses, as they showed similar mean values in echolocation clicks, BBPs and whistles, as well as similar variability as those obtained from sequences recorded with the other dolphin groups (see Figure S5). Among the 59 total sequential treatments that included a beacon emission sequence performed on 47 groups of dolphins, the acoustic responses remained similar, which suggests that dolphins might be able to increase their awareness of the surrounding situation. This could be confirmed by reproducing the experiment several times with the same groups, which is however almost impossible in the study area, and more broadly in the Bay of Biscay, given the spatio-temporal mobility of groups and the possible mixing of individuals among groups. Moreover, a "dinner-bell" effect might exist [7,13], and whilst it was not observed in our experiment, the addition of fishes in the nets could change the way dolphins react to the prototype's signal.

Carrying out tests during the fishing activities of professional gill netters will allow assessment of the practicality and efficiency of the new device. It started in 2021 with 12 days at sea surveyed by scientific observers onboard two gill net fishing vessels simultaneously, and it continued in 2022, with 228 days between February and the end of August onboard four vessels more or less simultaneously, resulting in a total of 1043 fishing operations. During these observations, five dolphin by-catches were reported: two individuals entangled within nets not equipped with beacons and three within equipped nets. One of the two by-catches reported within a gill net not equipped with beacons at the end of July (200 m long, set at the seabed at about 3 to 6 metres, caught at about 50 m from the net extremity) was released alive (thus probably caught when the net was starting to be released out of the water). A dolphin by-catch was reported at the end of August within an equipped net, but it was set into water accidentally during ten days by the fishermen for technical reasons. This led the battery of the beacons to be discharged (autonomy of about seven days), knowing also that beacons were used during three days before this fishing operation without being recharged in the meantime. In addition, two by-catches of common dolphin were reported at the end of July, within two different gill nets equipped with three bio-inspired beacons (4 km long, 1.5 metres high, set at the seabed at about 24 and 26 metres, respectively). The distances of these by-catches to the closest acoustic beacon were 500 m and 1000 m, respectively. In theory, and given the source level of the beacon, the high-frequency part of the emitted signal is preserved up to a maximum of 500 m. While the low-frequency part of the signal propagates further, it was estimated that a device has to be set every 1000 metres along the net, knowing that 500 m is the maximum distance so that the whole frequency range (20–200 kHz) of the signal emitted by a beacon is preserved. In addition, for practical reasons, on each of these nets, three acoustic devices were set up using buoys placed on the top of the net (two surface buoys at the ends of the net, one buoy in the middle near the top rope of the net). This layout means that the signals were emitted "downwards" (i.e., towards the net) instead of the advocated "upwards" transmission from the lower part of the net. The closest acoustic beacon from each of these by-catches was the one placed in the middle part of the net. Given all these characteristics and this configuration, the signals emitted by the beacon placed in the middle of the fishing net, relatively close to the seabed, might not have been perceived by the dolphins at a distance of 500 m and 1000 m, depending on the direction from which they came.

It should be noted that according to available data, the estimated probability of dolphin by-catch by gill netters is considered to be low (i.e., 0.006 specimens per day at sea [102], or around 0.015 specimens per fishing operation [103], making a by-catch report by scientific observers potentially rare. The overall level of estimated by-catch numbers in the Bay of Biscay by gill netters (see Section 1) is thus likely to be induced by the numbers of vessels in activity, which is estimated to be around 400 French boats, and about half this number for foreign vessels [104]. Statistically robust tests of device efficiency in reducing by-catch would thus involve a strong observation effort as well as being focused on a spatially restricted zone in order to cover a fishing fleet if possible. Moreover, knowing the way that dolphins calmly left after signals were emitted by the bio-inspired acoustic beacon, tests have to be conducted with professional fishermen using a gill net, which is passive, and not with pair trawlers. The latter deployed active fishing gear at 2–4 knots, about 200 m long, with an opening of about 200 m by 50 m. For this fleet, which might represent about 5% of common dolphin by-catches in 2019 [23,105], repellent pingers currently seem to be the most effective way to reduce by-catches, i.e., by 65% on average (CI: 15–98%) [32]. A complementary means to assess dolphin behaviour and to assess the potential of the prototype in limiting by-catch will be to study dolphin's positioning in 2D/3D from acoustic recordings around nets during fishing activities, with and without emission of the bio-inspired beacon. A forthcoming experiment using five hydrophones on autonomous silent marine drones will enable us to record with precision signals coming from animals [106] and to estimate their spatio-temporal trajectories around a fishing net [107]. It will help in understanding the prototype's effects on dolphins when they are faced with the different steps of setting, fishing, and withdrawal of a net by professional fishermen.

Current technological developments of the bio-inspired beacon are focused on improving its ergonomy for gillnetters (smaller and lighter) as well as to emitting more faithfully, i.e., with minimal noise, the signal initially recorded during a dedicated experiment (signals corresponding to returning echoes from echolocation clicks of a common dolphin performed on a fishing net, and a fishing net with a dead dolphin in it). Future experiments at sea will assess dolphins' responses to this improved device. In addition, starting September 2022, the bio-inspired acoustic device will include passive listening in order to emit signals when dolphins are detected in the area, thus limiting acoustic pollution. Limiting signal emissions will also contribute to a decrease in energy demand and will increase device autonomy. Looking further ahead, this new bio-inspired beacon could potentially be used to limit by-catches of other odontocetes species. This would only require integrating dedicated signals into the device.

To conclude, results based on visual surface observations and acoustic recordings highlight that bio-inspired signals emitted from a new acoustic beacon provide promising means to signal the presence of fishing nets to common dolphins and potentially to limit by-catch. According to future results of the 2D/3D behaviour of dolphins obtained from acoustic recordings around fishing nets equipped with and without the device, as well as practicality and efficiency tests with professional fishermen, the approach of a bio-inspired beacon might be an alternative, or a complement in some cases depending on the type of fishing gears, to the use of repellent pingers in order to limit the by-catch mortality of odontocetes worldwide.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su142013186/S1. Figure S1: Detected acoustic responses of dolphins during each day of the sampling campaign, for each type of signal emitted by dolphins. Figure S2: Detected acoustic responses of dolphins in relation with the presence of a fishing net underwater for each type of signal emitted by dolphins, Figure S3: Detected acoustic responses of dolphins in relation with the fishing net that was put in the water for each type of signal emitted by dolphins, Figure S4: Detected acoustic responses of dolphins in relation with the signal emitted by the bio-inspired beacon for each type of signal emitted by dolphins. Figure S5: Detected acoustic responses of dolphins according to the ID group, for each type of signal emitted by dolphins. Table S1: Signification of codes associated with signals emitted by the acoustic beacon. Table S2: Intensity of response of observed dolphin behaviour according to the signals emitted by the bio-inspired beacon.

Author Contributions: Conceptualisation, B.M., H.G., L.L., O.V.C., A.P. and Y.L.G.; methodology, B.M., H.G., L.L., O.V.C., W.D., A.P., K.P., Y.L.G. and E.M. (Eric Menut); software, L.L., H.G. and B.M.; validation, B.M. and H.G.; formal analysis, L.L., H.G. and B.M.; data acquisition, B.M., O.V.C., J.S., H.P., E.M. (Eleonore Meheust), W.D., A.P., K.P., Y.L.G. and E.M. (Eric Menut); data curation, B.M. and L.L; writing—original draft preparation, L.L. and B.M.; writing—review and editing, all authors; visualisation (figures production), L.L., B.M. and O.V.C.; supervision, B.M. and H.G.; project administration, B.M.; project funding acquisition, B.M., S.B., O.V.C., J.S., W.D., A.P., Y.L.G., Q.S. and T.R. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: The DOLPHINFREE project had (i) agreement #0-12520-2021/PREMAR_ATLANT/AEM/NP from the French Maritime Prefecture of the Atlantic "to conduct a survey for monitoring groups of common dolphins by means of scientific instruments off the south Finistère coast, following Décret n°2017-956 of the scientific marine research", (ii) favourable notification from the Ethical Committee in Animal Experiment of Languedoc Roussillon (CEEA-LR) for request #26568 "Behavioural study of wild dolphin groups in response to acoustic signals for limiting by-catch from professional fishery".

Informed Consent Statement: Not applicable.

Data Availability Statement: Acoustic recordings contain elements of intellectual property (i.e., signals emitted by the bio-inspired beacon) and are therefore not provided. Scripts and processed data are available at https://gitlab.lis-lab.fr/loic.lehnhoff/Scripts-DOLPHINFREE (accessed on 12 October 2022).

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Abbreviations

The following abbreviations are used in this manuscript:

BBP	Buzz and Burst-Pulse
ICI	Inter-Click Interval
SR	Sampling Rate
STD	Standard Deviation
BEF	Before beacon activation
DUR	During beacon activation
AFT	After beacon activation
NB GLM	Negative Binomial Generalised Linear Model
ZINB	Zero-Inflated Negative Binomial model

Appendix A. Projection of Clicks

During the identification of echolocation clicks, it was necessary to discriminate true clicks (emitted by dolphins) from false clicks (emitted by the boat's sonar when it was forgotten to turn it off during experiments) in order to discard them from the analyses. To do this, a 2D projection of detected clicks was used by means of an Uniform Manifold Approximation and Projection for Dimension Reduction (UMAP) [67] with three features per clicks classified: mean frequency, median frequency and frequency standard deviation. UMAP is an efficient grouping method for big datasets [67]. It works similarly to t–Stochastic Neighbour Embedding [108] producing equally meaningful projections but faster [109], using graph layout algorithms to arrange data in low-dimensional space. Results from UMAP underlined two groups of signals that did not come from dolphins (Figure A1). These groups mainly contain clicks from 12 July 2020 and 9 July 2021, corresponding to days when the sonar was turned on. Therefore, it was identified that one group corresponds to clicks from sonars (bottom-right) and the other one corresponds to echoes associated with them (top-right). Ultimately, only the clicks from the remaining group (left), which contains 195,153 clicks, were kept for further analyses of dolphins' signals.

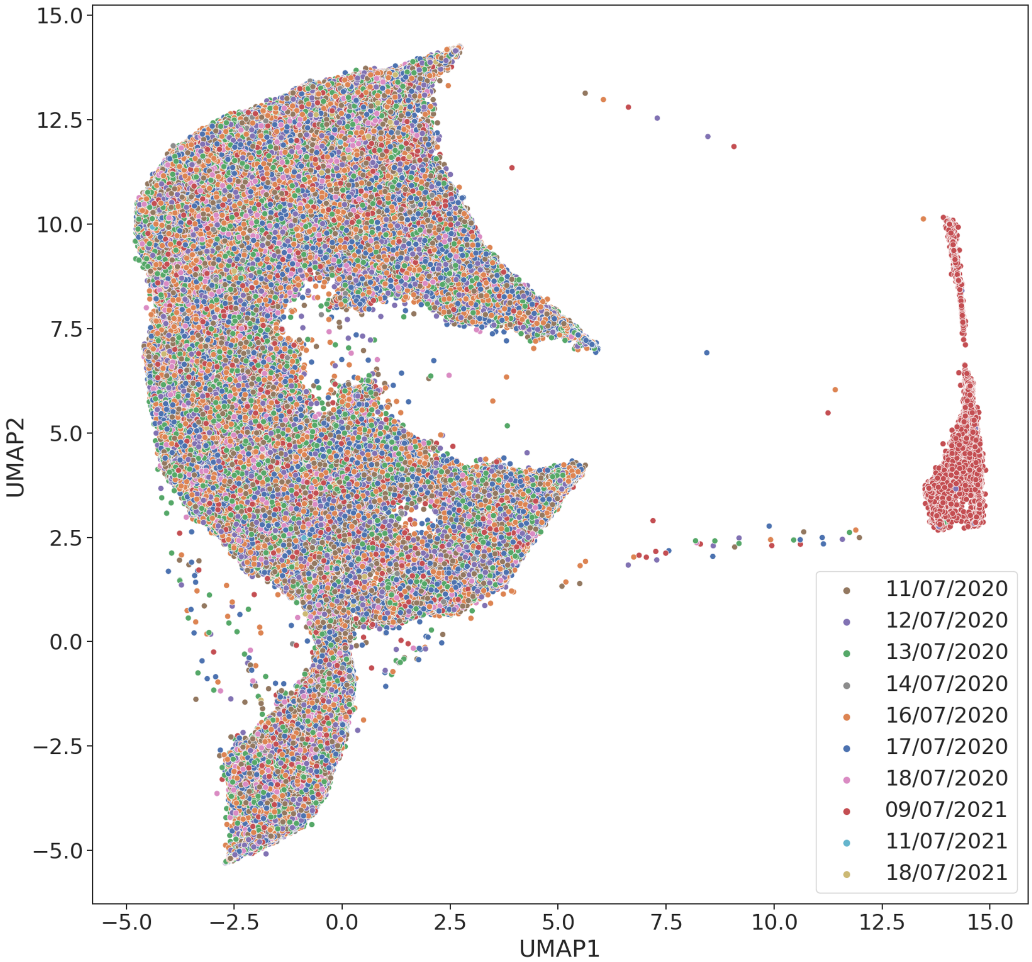
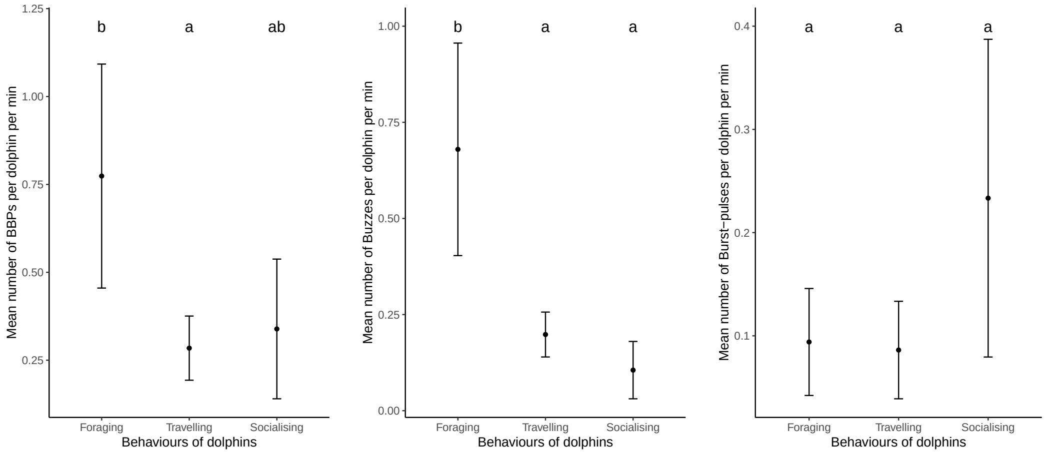


Figure A1. UMAP 2D-projection of 211,800 detected echolocation clicks based on three features: mean frequency, median frequency and standard deviation. Coloured according to day of recording.

Appendix B. Buzz and Burst-Pulse Characteristics

We grouped buzzes and burst-pulses under the name "BBPs". They are similar by definition (pulsed sequence of clicks) but, as already mentioned, have different functions for dolphins. By means of manual identification, we identified 570 buzzes and 231 burst-pulses with mean ICIs of 403 ms and 138 ms, respectively. These values are comparable to those found in other studies [55–62].

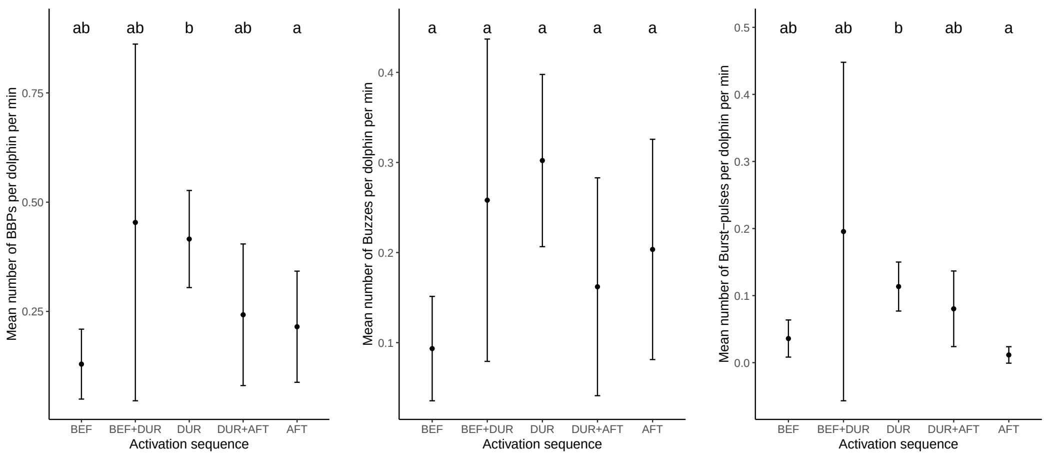
A statistical analysis was computed on buzz and burst-pulse separately. Naturally, they did not vary in the same way among all modalities. In particular, the mean number of BBPs emitted per dolphin varied according to their behaviour phase (NB GLM, Chi2 = 11.4, df = 2, p < 0.001). More specifically, buzzes were emitted in higher quantities when dolphins were foraging compared to when travelling (Tukey post hoc test p < 0.01). Burst-pulses seem to have been emitted mostly during social interactions (see Figure A2), but no differences were highlighted (Tukey post hoc test p > 0.05). These results suggest that buzzes and burst-pulses have functional differences for common dolphins and may be used in different contexts.



(**a**) (**b**) (**c**)

Figure A2. Detected pulsed sounds of dolphins according to the group behavioural state observed in each group. Modalities with different letters have different mean values (H0 rejected by Tukey's post hoc test). Ranges show 95% confidence intervals. BBP data are aggregated from buzzes and burst-pulses. (**a**) Number of detected BBPs per audio per dolphin according to observed behaviour. (**b**) Number of detected buzzes per audio per dolphin according to observed behaviour. (**c**) Number of detected burst-pulses per audio per dolphin according to observed behaviour.

The sequential treatment underlined an effect on the mean number of burst-pulses (NB GLM, Chi2 = 10.3, df = 4, $p < 0.05$) but not on the mean number of buzzes (ZINB, Chi2 = 6.2, df = 4, $p > 0.05$) (see Figure A3). However, there was a difference between the mean number of buzzes recorded before the activation of the bio-inspired beacon (0.0934 per dolphin per minute) and during its activation (0.302 per dolphin per minute) (Figure A3). For burst-pulses, there was also an increase in mean between BEF and DUR (0.0360 and 0.113 per dolphin per minute), but it is at AFT that the mean number of detections was the lowest (0.0115).



(**a**) (**b**) (**c**)

Figure A3. Detected pulsed sounds of dolphins recorded during sequential treatments. Modalities with different letters have different mean values (H0 rejected by Tukey's post hoc test). Ranges show 95% confidence intervals. BBP data are aggregated from buzzes and burst-pulses.(**a**) Number of detected BBPs per audio per dolphin during each treatment sequence. (**b**) Number of detected buzzes per audio per dolphin during each treatment sequence. (**c**) Number of detected burst-pulses per audio per dolphin during each treatment sequence.

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