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Short Note

Incomplete Detection of Echolocation Click Train Patterns Compromises the Use of Single Porpoise Detectors in Studying Harbour Porpoise (*Phocoena phocoena*) Behaviour

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The harbour porpoise (*Phocoena phocoena*) is a small, open-water cetacean commonly found in coastal regions in the northern hemisphere (Read & Westgate, 1997). They are often described as "shy" creatures and generally seem to be sensitive to human disturbance (Olesiuk et al., 2002). Harbour porpoises appear at the surface for short periods of time and, hence, are difficult to track visually (Kyhn et al., 2008). They travel in small groups, with an average group size of approximately two (Palka, 1995), but many other aspects of their behaviour are unknown. Harbour porpoise habitat includes the Bay of Fundy, Canada, where this study was performed. Harbour porpoises regularly swim between salmon aquaculture cages, especially at night, but their behaviours there have not been documented (Haarr et al., 2009). A preliminary study found that time vs inter-click interval (ICI) plots of echolocation click trains could be automatically extracted from individual harbour porpoise echolocation click detector (i.e., T-POD) data sets and categorized using cluster analysis programs. This raised the possibility of identifying stereotyped ICI click train patterns, which, through further study, may be linked to specific behaviours. As a preparatory step to determine if echolocation click train patterns can be used to index various behaviours, it was necessary to determine if data from a single porpoise detector or acoustic data logger could be used to classify click train patterns or if any missing portions would compromise the resulting pattern shapes.

Harbour porpoises use echolocation on a regular basis, but the rates are variable (Akamatsu et al., 1994). In addition to foraging and navigation functions, harbour porpoise echolocation click trains can be used for communication (Amundin, 1991; Koschinski et al., 2008; Clausen et al., 2010). The echolocation click frequency ranges from 100 to 160 kHz with the central frequency between 129 to 145 kHz (Møhl & Andersen, 1973; Au et al., 1999; Teilmann et al., 2002; Villadsgaard et al., 2007). The echolocation pulses of harbour porpoises have a beam angle, based on the 3 dB down beam width of ~16.5° or narrower (10.7° to 13.1°) both horizontally and vertically (Au et al., 1999; Koblitz et al., 2012). However, changing the beam width criterion to 9 dB down results in a beam angle of ~25°, and 20 dB down results in a beam angle of > 40° (Au et al., 1999; Koblitz et al., 2012). The greater the angle between the direction of the harbour porpoise and the receiver, the lower the received level will be. The beam can be manipulated somewhat using the air sacs and fatty melon inside the head of the harbour porpoise (Au et al., 2006). One consequence of the narrow beam pattern is that the echolocating harbour porpoise must be generally facing a passive acoustic monitor in order to be detected. Directional changes while swimming can result in the echolocation pulse train sweeping across a receiver, which would thus only detect a portion of the pulses (Koschinski et al., 2008; Verfuß et al., 2009; Akamatsu et al., 2010). Thus, there will be a complex interaction between the distance, direction, and movement of the harbour porpoise; the source level of the echolocation clicks; the sound transmission properties in the area; and the sensitivity of the receiver.

Harbour porpoise presence has been studied using passive acoustic monitoring, especially through the use of T-PODs and later version C-PODs (Chelonia Ltd., UK) (Verfuß et al., 2007; Kyhn et al., 2008). A T-POD or C-POD is a data logger that is designed to detect high-frequency (130 kHz), narrow-band harbour porpoise echolocation clicks (Tregenza, 2012). T-POD and C-POD systems contain a hydrophone, analogue processor, digital logging system, and software that extracts the echolocation clicks using a detection algorithm. It collects echolocation data by logging the time of each click with 10 μs resolution. The active space for harbour porpoise echolocation clicks is estimated to be up to a maximum of 1 km (Clausen et al., 2010), but the effective detection ranges by T-PODs are likely in the order of 100 to 500 m, depending upon the sensitivity of the individual T-POD, click train classification settings, and sound transmission losses (Kyhn et al., 2008, 2012).

Beyond providing basic presence or absence data in an area (Haarr et al., 2009; Todd et al., 2009; Scheidat et al., 2011), passive acoustic monitoring using T-PODs, or later model C-PODs (Chelonia Ltd., UK), shows promise for studying harbour porpoise density (Kyhn et al., 2012), foraging (Verfuß et al., 2009), navigation (Akamatsu et al., 1995), threat (Nakamura et al., 1998), and communication behaviour (Koschinski et al., 2008). Click train patterns are the shapes depicted by scatterplots of the ICIs or clicks per second over time since the start of the click train is depicted as either click number (Akamatsu et al., 1995) or time (Clausen et al., 2010). For example, while capturing live fish, the click trains begin with an approach phase with constant ICIs of about 50 msec that is followed by a sudden drop in ICIs and ends with a terminal buzz of ICIs of about 1.5 msec (Verfuß et al., 2009). Nakamura et al. (1998) and Clausen et al. (2010) provide evidence that harbour porpoises communicate acoustically using specific patterns of clicks. Koschinski et al. (2008) link some click train ICI pattern shapes to behavioural categories that included feeding, approach behaviour, and possibly distress. They note, however, that sometimes only fragments of click trains are logged because of the narrow echolocation beam and movements of the harbour porpoise. When this happens, it is likely that some of the partial click trains could be erroneously assigned to different patterns of clicks and ICIs that were actually produced, which in turn could lead to the assignment of an incorrect behaviour (Koschinski et al., 2008). The magnitude of this potential problem is unknown. In this study, three T-PODs were deployed 6.4 m apart (see below) to record harbour porpoise click trains. The goals were to determine if it would be practical to use a single T-POD or C-POD for detection of click train patterns and if any missing portions would be likely to result in a misclassification of the click train pattern shapes—that is, would missing portions of a click train occur significantly often to bias a study using click train ICI patterns to elucidate harbour porpoise behaviour? If not, it should be possible to identify stereotyped ICI patterns of harbour porpoises (if they exist) and ultimately link some patterns to specific behaviours. This, in turn, would facilitate using T-PODs or C-PODs to study harbour porpoise behaviour at times and places where direct observations are not possible.

The study site was an Atlantic salmon (*Salmo salar*) aquaculture cage site in Charlie's Cove in the Bay of Fundy, Canada (45° 01' 47.79" N, 66° 52' 01.19" W). The cage site is located near the mouth of Back Bay. Previous data indicated relatively high porpoise presence during the summer (J. M. Terhune, unpub. obs.). This site was selected because it was secure from vandalism; harbour porpoises were known to be present; and the T-PODs on ropes with small anchors could be easily deployed and retrieved from a flotation ring of one of the aquaculture cages. The behaviour of the harbour porpoises within the cage site was also of interest.

Data for this study were collected from 17 June to 21 July 2010. The aquaculture site had no fish in the cages during the study period but had been utilized the year before for salmon farming. There were salmon cages approximately 5 m apart and three mussel rafts at the cage site (Figure 1). Each cage was held in place by four sets of four steel cables from each of four anchors running up to the flotation ring at the surface. Three T-PODs were submerged to a depth of 4 m from the outside of the flotation ring along the perimeter of a 100-m circumference cage (Figure 1). The cage netting was suspended vertically ~1 m behind the T-PODs and was approximately 15 m deep. The water depth was 20 to 30 m. The ropes holding the T-PODs were tied to vertical netting supports that were separated by 6.4-m intervals along the curved line of the flotation ring of the aquaculture cage. The linear distance between the terminal T-PODs was 12.5 m. The harbour porpoise could only approach the array over a ~220° arc. The T-POD on the right (facing the cage) was closest to an open water area within the set of cages (Figure 1).

The T-PODs positioned on the left and middle were Version 7 (Serial Numbers 731 and 739, respectively), and the T-POD on the right (R) was Version 4 (Serial Number 435). We were unable to calibrate the sensitivities of the T-PODs. The internal clocks of all the T-PODs were initialized using the same computer. The exact clock drift of the T-PODs is unknown, but by comparing the times of matching click trains recorded within the same minute near the end of the study period, the greatest relative clock drift was estimated to be < 2 s/d. The pod settings file for all T-PODs was "porpoises only normal sensitivityV5.pds." The scan settings were all set to Target (A) filter frequency 130 kHz, Reference (B) filter frequency

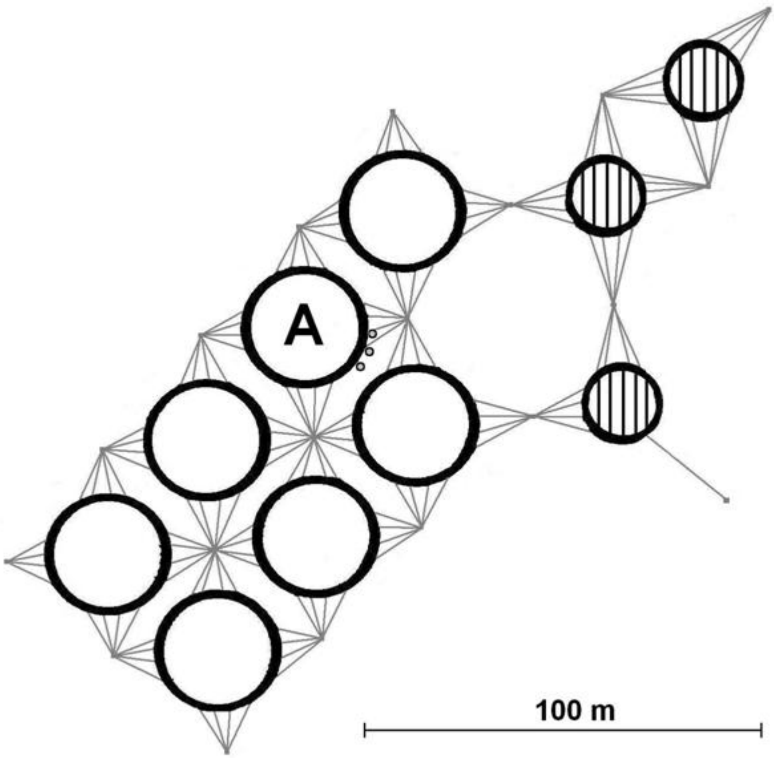


Figure 1. The aquaculture cages at the Charlie's Cove site showing the locations of the three T-PODs (small circles on the right of the cage marked "A") suspended at 4 m depth from the outer flotation ring of a salmon aquaculture cage (large circles) outside of the 15 m deep netting; nearby were three mussel rafts (smaller circles with cross bars). The cages and rafts were positioned by cables (shown in grey) attached to anchors. *Source:* A site map provided by the Cooke Aquaculture Company

92 kHz, Click bandwidth 4, Noise adaptation ++, Sensitivity 16, and Scan limit on N of clicks logged 240. These are standard default settings provided by the manufacturer. The system selects for clicks with high acoustic energy at 130 kHz and low acoustic energy at 92 kHz, a feature that identifies the spectrum of harbour porpoise clicks (Møhl & Andersen, 1973).

The battery level on the middle T-POD reached a preset minimum value after 33 d, 14 h, and 9 min of recording while the other T-PODs operated for a longer time. Hence, only data for 33.6 d could be analyzed from all three T-PODs. Analysis was done using *TPOD.exe*, Version 8.24, set to "Cet all" (high and low probability cetacean trains). For each T-POD, the minute and time of each click (nearest 10 µsec) were exported to an *Excel* spreadsheet. A click train was identified by the analysis program as five or more click detections in a series. Click trains were tallied according to their occurrence (presence or absence only) in the same minute on the three T-PODs. The matching was done manually by searching through data from each T-POD for corresponding minutes. The total number of monitored minutes was 47,731, with 5,929 min (12.4%) containing click trains.

Except for the first day of deployment, click trains were detected every day, and the number of detections increased slightly toward the end of the study period. There was a strong diel pattern: 80% of the click trains occurred between 1900 and 0659 h. Of the 5,929 min containing click trains, 953 min had detections by all three T-PODs within the same minute (Table 1). These 953 min contained 1,788 click trains, but there were only 290 individual click trains that were pattern matched on all three T-PODs. The middle T-POD had the fewest detections overall and, thus, is thought to be less sensitive than the other two (as discussed below) (Table 1).

Using the spreadsheet with the sorted minutes, the minutes which contained click trains on all three T-PODs were extracted. For the 953 min that had detections on all three T-PODs, the time of every click within each click train was transformed into an ICI. For each click train within

Table 1. Detections of 1,788 harbour porpoise (*Phocoena phocoena*) echolocation click trains by the three T-PODs when all three T-PODs had detections within the same 953 1-min periods. The middle (M) T-POD was 6.4 m from the left (L) and right (R) T-PODs, and the left and right T-PODs were separated by 12.5 m.

	Detections within the same minute		
Receivers	Left	Middle	Right
LMR	290	290	290
LM	290	290	--
LR	53	--	53
MR	--	148	148
L only	320	--	--
M only	--	225	--
R only	--	--	462

the same minute, the three ICI columns, one from each T-POD, were visually scrutinized for matching patterns of ICIs. This permitted identification of the click trains detected by all three T-PODs.

Once a set of matching ICIs were found, the same ICI within each pattern was designated as time "0" with respect to the duration of the entire click train, and the times of the three patterns were arranged around this point. For example, in minute 269,474 (minutes since the beginning of the year), there were two adjacent ICIs of 2.91 msec recorded on all three T-PODs (Figure 2a). The patterns of each click train were matched by setting the first 2.91 msec ICI as time 0 on the time-adjusted scale (Figure 2b). There were five or more adjacent matching ICIs from each T-POD that were overlapped in each click train sequence adjacent to the ICI selected as the zero point. This procedure enabled matching overlapping portions of each click train so that a scatterplot of the complete ICI pattern could be depicted visually (Figure 2b). If no matching ICI patterns were evident, the click train patterns were deemed to have been detected by only one or two of the T-PODs.

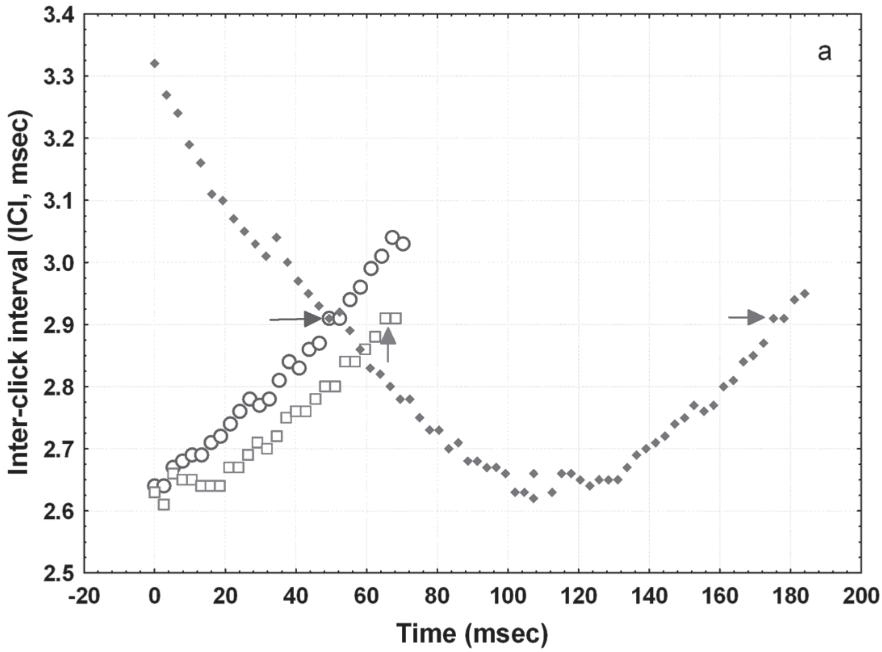
For each click train, the total number of ICIs from the first to last detection was determined. The proportion of ICIs detected by each of the three T-PODs was calculated. For example, in Figure 2b, the complete pattern had 71 ICIs, with 67, 26, and 26 ICIs detected by the right, middle and left T-PODs, respectively.

Each of the 290 time-adjusted scatterplots was printed showing the ICIs of each of the three T-PODs (as in Figure 2b). At present, only a few ICI patterns have been linked to particular behaviours (e.g., feeding buzz [Verfuß et al., 2009]; Table 2, Shape R), so a continuum of putative patterns was adopted to facilitate the analysis of the impact of missing parts of click trains on the pattern classifications. The authors classified each full echolocation ICI shape pattern into one of nine arbitrary shape categories, plus one undefined category. The patterns were arranged along a continuum beginning with constant (horizontal) ICIs throughout, to increasing ICIs, increasing then decreasing ICIs (inverted U shape), decreasing ICIs, and finally, decreasing then increasing ICIs (U shape). Either a zero or one inflection point was present in each pattern. The shapes were arbitrarily labelled alphabetically from M to U with a final category V, which included shapes too variable to fit into any of the other patterns (Table 2). The overall shape of the full pattern was used, and any second or third inflection points were not considered. That is, if a pattern began with a major horizontal segment, and then the ICIs increased prior to a slight decrease, the pattern was classified as Shape N. The next step was to classify the patterns presented by only one or two of the T-PODs and determine if there was a shape change. For example, for the pattern depicted in Figure 2b, if the full pattern was classified as Shape U, but for two of the three T-PODs (left and middle) it was classified as Shape O, then a shape classification change occurred.

Of the 290 click train patterns that were identified on all three T-PODs, the presumed full patterns were only detected for 23 by the middle T-POD, 36 by the left T-POD, and 145 by the right T-POD. The proportions of clicks per full click train recorded by each T-POD were 76.5 ± 21.0% (mean ± SD), 81.5 ± 20.7%, and 88.5 ± 16.8% for the middle, left, and right T-PODs, respectively. Many of the patterns also contained a number of ICIs below 2.0 msec, which corresponded to reflections off the aquaculture cage netting based on the two-way transmission time. These echoes were disregarded in the analyses. The mean click train duration of the 290 click trains was 529 ± 539 msec and the mean ICIs were 20.2 ± 44.8 msec.

It is possible that some of the click trains may have resulted from two harbour porpoises echolocating simultaneously. This is unlikely to have happened often, particularly in the 290 patterns received on all three T-PODs, because the individual ICI patterns would have to overlap equally on all three T-PODs over the five or more adjacent ICIs that were used to time align the three patterns.

Compared to the classification of the ICI patterns of the "full" echolocation click trains, as recorded by all three T-PODs, 9% of the patterns were misclassified into three different patterns if inspected on only one of the T-PODs, and 13% into two patterns if inspected on two of the T-PODs. The three shapes that did not have an inflection point, Shapes M, O, and S, were classified as being in the same groups for all three



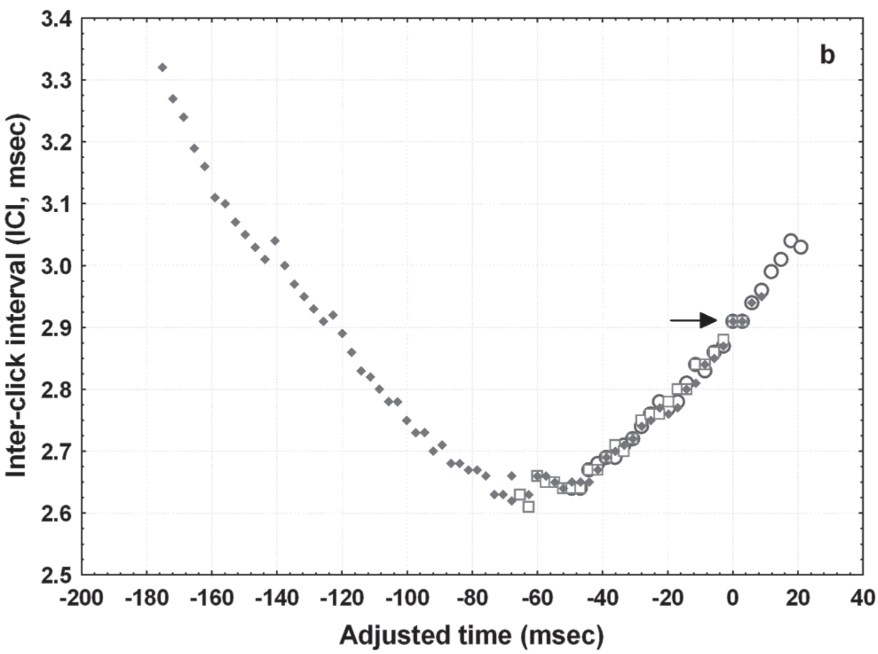


Figure 2. (a) The inter-click interval (ICI) times of a harbour porpoise (*Phocoena phocoena*) echolocation click train recorded within the same minute on each of three passive acoustic monitors (T-PODs; left **o**, middle □, and right ♦; see text); the arrows indicate a pair of matching ICIs of 2.91 msec on each of the three T-PODs. (b) A harbour porpoise ICI pattern after being time aligned by matching the first of the pair of ICI of 2.91 msec (arrow); the harbour porpoise echolocation click train apparently swept the three T-PODs from right to left.

Table 2. Changes in the classification category of harbour porpoise click train patterns when considering data from three T-PODs vs one or two T-PODs; note that Shape V (no shape) was excluded because by definition it cannot change in shape. Numbers in brackets are the percentage of cases in which all three T-PODs exhibited the same shape pattern.

Shape		Total	Same pattern on all 3 T-PODs	Same pattern on 2 T-Pods	Different pattern on each T-POD
M	—	97	93 (96%)	2	2
N	=/	17	10 (59%)	6	1
O	/	23	22 (96%)	1	0
P	/‾	7	4 (57%)	2	1
Q	/\	39	21 (54%)	8	10
R	‾\	6	5 (83%)	1	0
S	\	17	15 (88%)	1	1
T	\=	35	21 (60%)	9	5
U	\/	31	22 (71%)	4	5
Total		272	213	34	25
% Total		100%	78%	13%	9%

T-PODs in 88 to 96% of the cases (Table 2). All other patterns contained an inflection point, and the pattern shape as detected by at least one of the three T-PODs was different than that of the full pattern in 54 to 83% of the cases (Table 2).

The right T-POD detected more click trains overall and more complete click trains than the left or middle ones. This T-POD was located closest to the open water area within the cage site and would have been less shadowed than the other two receivers. The middle T-POD detected the lowest number of complete click trains. The left T-POD was adjacent to a more confined and smaller area than the right one and detected an intermediate number of complete click trains. This suggests that the sensitivity of the middle T-POD was lower than that of the other two. In part, this would account for the middle T-POD having a slightly lower proportion of clicks per full click train detection than the other two T-PODs. There were 53 of 1,788 click train patterns that were matched on the left and right T-PODs that were not detected by the middle T-POD (Table 1). Even if the sensitivities of the T-PODs were known, it would not be possible to correct for any missing portions of a click train. Whenever the receivers are on the edge of the echolocation beam, the lower sound levels will result in a greater proportion of missed detections by the less sensitive systems. In this study, 9% of the received patterns had different shapes on each of the T-PODs, suggesting that in addition to the sensitivity of the receivers, the myriad of combinations of directivity and amplitude of the echolocation beam, and the orientation and distance of the harbour porpoise relative to the array will affect the detectability of the complete click trains.

The use of three adjacent receivers greatly increased the probability of detecting the actual start and end of the 290 click train patterns. It is possible, however, that a harbour porpoise may have abruptly turned away from the array before completing the entire click train. Thus, the measures of proportions of clicks missed by a single receiver and subsequent shape misclassifications reported herein may be underestimated.

The wide variety of ICI pattern shapes and times made it difficult to identify natural stereotyped patterns. A detailed analysis and classification of the pattern shapes likely would have resulted in an even greater number of shape categories and was beyond the scope of this study. The predetermined shape categories followed a continuum from horizontal to rising to decreasing ICI interval patterns, and some of the individual pattern shapes could well have been placed in an adjacent category. The limitation of a single inflection point further simplified the classification system. Some of the pattern shapes reported herein have been presented by Koschinski et al. (2008) and Clausen et al. (2010) with both of these studies providing figures of click train ICI patterns that have more than one inflection point. It is likely that a very large number of click train patterns will have to be documented before it will be possible to develop a categorization system based on natural recordings.

Half of the click trains received by the right T-POD were incomplete, and the proportion was much higher for the other two receivers. As a consequence, many of the click trains classified into shape categories with an inflection point would have been misclassified if only a single receiver was used. There was little impact on the M, O, and S classifications as these were constant shape categories which would not change if portions of the start or end of a click train were removed. For the more complex pattern shapes with one or more changes in ICI decreasing or increasing inflection points, there would be a much greater chance of misclassification. The shape misclassifications could result in different interpretations being assigned to the behavioural functions of the communicative function of the click trains. For example, Figure 11b in Koschinski et al. (2008) shows two "U" shaped calls that would appear as "\" shaped patterns if the last third of the click train was missed. If this were to happen, the linking of a particular ICI pattern to a specific behaviour could be compromised. Therefore, our goal of determining if a single hydrophone porpoise detector could be used to index harbour porpoise behaviour based on click train shape patterns has not been substantiated.

The initial goal of studying harbour porpoise behaviour within aquaculture cage sites resulted in the harbour porpoises being in very close proximity to the T-PODs. Thus, many click trains were only detected on a single T-POD. In open water situations, and with the harbour porpoises more often at a greater range, it is likely that individual T-PODs would detect a higher proportion of the complete click trains. The extent of how this would impact the identification and classification of complex ICI patterns is yet to be determined.

T-PODs, the newer C-PODs (Tregenza, 2012), and other acoustic monitoring devices are useful instruments for passive acoustic monitoring of harbour porpoise via detections of their high-frequency, narrow beam click trains. Movement and the narrowness of the harbour porpoise echolocation beam (Au et al., 1999; Koblitz et al., 2012) in many cases will result in an incomplete detection of the entire click train. When this occurs, the apparent shape of the ICI patterns of the click train may not be the same as that of the entire click train. The proportion of incomplete or misclassified ICI patterns will vary with the location and behaviour of the harbour porpoises. In this study, close to half of some ICI patterns would have been misclassified if data from only a single T-POD were used. This factor will have to be considered when using echolocation click train patterns in harbour porpoise behavioural studies.

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