PAPER

Bilateral bioacoustics research of Chinese freshwater dolphins

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Abstract: China has various ecologically important sites that provide wonderful research opportunities. The biosonar behavior of Yangtze finless porpoises (*Neophocaena phocaenoides asiaeorientalis*) in the semi-natural reserve, Hubei, China has been extensively studied for the past five years by the Japan Fisheries Research Agency and Institute of Hydrobiology, Chinese Academy of Sciences. Careful scanning and acoustical autofocusing behavior in porpoises was firstly observed in free-ranging conditions. The biosonar model obtained in this study allowed us to recently develop a broadband high-resolution sonar system called the Dolphin Sonar Simulator. Frequent biosonar production by finless porpoises also allowed an effective passive acoustical survey to be conducted of the animal along the entire habitat of this species in 2006. Bilateral collaboration with cutting-edge acoustical technologies was proven to be highly productive for basic behavioral science, engineering applications, and the conservation of endangered species.

Keywords: Finless porpoises, Bioacoustics, Biosonar, Echolocation

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1. INTRODUCTION

The sonar abilities of dolphins and porpoises have been extensively studied [1]. Not only can these animals detect a remote target using sonar, but they can also precisely discriminate its size, thickness and material composition [1]. In addition to controlled captive experiments, sonar signals of wild dolphins and porpoises have been examined [2–4] sonar signals of dolphins and porpoises consist of high-intensity and high-frequency ultrasonic pulse trains that stand out well against ambient noise even in the wild [5]. The number of ultrasonic pulses emitted is considered an appropriate indicator of the search effort made by an animal. Moreover, the target range of the sonar used by dolphins can be estimated from the interclick interval [1,6]. These signals can easily be recorded and can provide information about the timing and the distance over which the echolocating animal uses its biosonar. This makes dolphins and porpoises some of the most appropriate model organisms in which to observe biosonar behavior in the wild.

However, the problem of recording the sonar signals of free-ranging dolphins and porpoises simultaneously with underwater behavior has remained largely unsolved. Hydrophone systems can observe individual vocalizing

cetaceans for only a limited time and they record little behavioral information [2,7,8]. A mobile video camera carried by a human diver can record behavior and vocalizations only during brief encounters with the animals [9]. Although underwater sound recording systems have recently been attached to large marine mammals [10–13], few studies have been successful in recording ultrasonic sonar signals concurrently with the underwater behavior of individual dolphins and porpoises [14–16]. Furthermore, none of the data logger systems attached to these animals can distinguish vocalizations from those of other nearby individuals. These data logger systems for recording vocalizations are therefore inappropriate for studies of animals that swim in groups, such as dolphins and porpoises.

To investigate the biosonar behavior of aquatic animals, we developed a miniature stereo acoustic data logger (*A-tag*) and used it on eight free-ranging porpoises in an oxbow of the Yangtze River, China. Time-sequence data of sonar events and underwater behavior were recorded for individuals. In addition, the direction of the sound source was stored in the data logger in order to exclude sonar signals from other individuals. Here, we examine the acoustic activity and behavior of free-ranging echolocating finless porpoises in a large open-water system.

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2. METHODS

Until 1972, the experimental site was a tributary of the Yangtze River, and water still enters from the main stream during every flood season [17]. This oxbow lake, part of the Tian-e-Zhou Baiji National Natural Reserve of the Yangtze River, Hubei, China (29.47'–29.51'N, 112.32'–112.37'E), is approximately 21 km long and 1 to 2 km wide. It was established by the Chinese government in 1992 as a reserve for baiji (*Lipotes vexillifer*) and finless porpoises. Since 1990, 49 finless porpoises have been introduced from the main population in the river. Finless porpoises in the lake survive without supplemental food and are observed to reproduce annually. The environment of the lake is considered to be similar to the natural habitat of this species [18].

A-tag, a miniature stereo pulse event recorder (W20-AS, Little Leonardo, Tokyo, Japan, diameter: 22 mm; length: 122 mm; weight: 77 g) was developed for this research. Its dynamic range is between 129 dB and 157 dB peak to peak (reference pressure 1 μ Pa at 1 m). The resolution of the time difference was 542 ns. Simultaneously, swim speed, dive depth, heaving and surging body acceleration were recorded with a behavior data logger (diameter: 21 mm; length: 114 mm; weight: 60 g, PD2GT, Little Leonardo, Tokyo, Japan).

Nine finless porpoises were captured in the reserve in October 2003. All animals were safely captured and released with data loggers after this period. The data logger was fixed to the side of the body in the upper posterior direction from the pectoral fin; this area was the least affected by body movements and therefore ensured a long attachment time. Recording the sonar signals of finless porpoises was possible at this position even for off-axis sound detection [15]. The time-sequence data from the acoustic and behavior data loggers were synchronized by the time stamp of the data file. Low-intensity signals below 136 dB, such as surface reflection, were excluded by off-line analyses using new custom-made software on MATLAB (The MathWorks, Massachusetts, USA) and Igor (WaveMetrics, Oregon, USA). We calculated the swimming speed in meters per second from the rotation of the propeller deployed in the behavior data logger using the methods of Fletcher *et al.* [19].

3. RESULTS

We recorded the biosonar behavior as well as the underwater body movements of eight finless porpoises. The simultaneous recording time of the acoustic and behavioral parameters varied from 1 h to 35 h for each individual (average 8.75 h). In total, we identified 2,425,095 pulses, 49,470 pulse trains and 5,113 dive events. The porpoises produced pulse trains on an average of every 5.1 s.

Fig. 1 Periods of silence in sonar signal records for a finless porpoise. The time series of the sound pressure (SP) shows periods of silence between pulse trains indicated by horizontal bars. The distance inspected acoustically was calculated from the interclick interval (ICI) of a train prior to the silence.

Many periods of silence between pulse trains were recorded (Fig. 1). Silent periods sometimes lasted for more than 10 s, whereas the swim speed during these periods ranged up to 3 m/s with an average cruising speed of 0.89 m/s. Because the underwater visibility in the lake is less than 1 m due to turbidity, the porpoises could not detect any remote obstacles in front of them without using sonar. The distance over which an animal traveled silently was calculated by multiplying the duration of every period of silence by the simultaneously recorded swimming speed.

We also calculated the distance inspected acoustically by the animals just prior to a period of silence. The acoustically inspected distance is given by the two-way distance traveled by sound within an interclick interval. However, in cetacean biosonar systems, an additional lag time is required within each interclick interval for the animal to process returning echoes (Au, 1993). This means that dolphins and porpoises do not produce sonar clicks when they receive an echo. They wait during the lag time before producing the next click. The lag time should be less than the shortest interclick interval. The minimum accumulated distribution of the interclick interval in a pulse train was 1 ms (Fig. 2(a)). This is the lower limit of the measurement of the interpulse interval because a 0.5 ms interval identical with the sampling interval of the recording system is eliminated in the off-line analysis. The lag time in our study was conservatively assumed to be no more than 5 ms, since the frequency of click occurrence dropped sharply below this interval. The left vertical dotted line corresponds to the 5 ms interval (Fig. 2(a)). The sample number of the data showed mountain-shaped

Fig. 2 Distance traveled in silence and the distance previously inspected acoustically. (a) Distribution of the average interclick intervals in pulse trains of eight finless porpoises. In 90% of cases, the acoustically inspected distance was less than 77 m. (b) Distance inspected acoustically was far greater than the distance subsequently traveled in silence. The gray scale shows the number of observed pulse trains in each bin. Most click trains fell under the diagonal line, indicating that porpoises inspected an area ahead for long enough before silently swimming into it.

distribution over 5 ms. However, it decreased to below 5 ms on approaching the lower limit of the time resolution of the interval. The upper inset of Fig. 2(a) shows the scale of the calculated distance inspected acoustically. The distance inspected acoustically in advance was far greater than the distance traveled silently (Fig. 2(b), accumulated data from all monitored individuals). This relationship was consistently observed for all individuals. In 90% of all cases, the

Fig. 3 Distance traveled during the approach phase and the change in the distance inspected acoustically. (a) The approach phase (arrow) is characterized by a linear decrease in the interclick intervals (ICI) of the sonar signals. The swimming speed dropped to nearly zero after the approach phase. (b) The distance traveled during the approach phase was closely correlated with the estimated change in the distance inspected.

acoustically inspected distance was less than 77 m and the modal focal distance was 24 m.

Once a porpoise detected a potential target and approached it, the animal often emitted clicks with a linearly decreasing interclick interval, hereafter termed the approach phase (Fig. 3(a)). Changes in the inspected distance from the beginning to the end of the approach phase were calculated from changes in the interclick interval. Additionally, the distance traveled during the approach phase was calculated by multiplying the duration of the approach phase by the swim speed (Fig. 3(b)).

Finless porpoises changed the inspected distance by 11.0 m on average (maximum 42.7 of the 117 approach phases analyzed) and swam 8.6 m on average (maximum 43.0) during the approach phase. These two independent parameters the distance traveled and the distance inspected during the approach phase were well correlated (Fig. 3(b); $r = 0.80$, $p < 0.005$).

At the end of the approach phase, the minimum interclick interval was near the assumed lag time (5 ms). A few seconds after the end of the approach phase, the swim speed frequently dropped to zero (see swimming speed profile in Fig. 3(a)).

4. DISCUSSION

The finless porpoises observed in this study produced sonar signals nearly constantly, on average every 5.1 s. This result suggests that the finless porpoises strongly rely on their acoustic sensory systems for navigation, traveling and capturing prey.

When moving through an environment in which vision is limited, prior acoustic inspection of the area ahead is essential for these animals. This strategy offers substantial advantages both in terms of risk avoidance and prey capture. In particular, animals must detect potentially lethal risks as early as possible. For example, harbour seals have been shown to avoid the long-range vocalizations of killer whales, their primary natural predators [20]. Potential risks for finless porpoises in a freshwater habitat include injuries from or entanglement in underwater debris and entrapment in shallow waters, as well as rough water surfaces or floating debris that prevent safe respiration. Taking such risks can be costly; thus, the porpoises must detect risks with sufficient time to avoid them by changing behavior. As shown in Fig. 2(b), finless porpoises almost always inspect upcoming areas for long enough before swimming silently into them. The porpoises seem to employ a large safety margin in their sonar range when inspecting the area ahead relative to the distance they swim silently.

During the approach phase, the porpoises seem to employ smaller safety margins, since the inspection distance is adjusted to the distance from a potential prey second by second. Once a porpoise detects an available resource ahead, it focuses the inspection distance on this target. In exchange for the small safety margin, a predator gains the advantage of locating the position of the moving remote prey well in advance.

Because animals face limitations in detection ability and because their search effort is time constrained, they must use their sensory systems appropriately. The finless porpoises in this study usually searched no more than 77 m ahead (Fig. 2(a)), a distance that could be reached within a couple of minutes at their typical cruising speed. Objects farther away are not important to the animal, regardless of

whether they are lethal or beneficial. Inspecting the immediate area through which a porpoise is going to travel allows time for decision-making before the animal faces real risks or rewards.

5. APPLICATIONS

Frequent biosonar production observed in the present study allowed effective passive acoustical survey of the animal along the entire habitat of this species. A towing hydrophone system was applied for the expedition of world-precious Chinese river dolphins (baiji) [21] and Yangtze finless porpoises (*Neophocoena phocoenoides asiaorientalis*) [22]. We searched the main stem of the Yangtze River between Yichang and Shanghai from 6 November through 13 December 2006 using visual and acoustic survey methods. Two research vessels towed stereo acoustic data loggers to store the intensity and sound source direction of the high-frequency sonar signals produced by finless porpoises at a range of 300 m on each side of the vessel. Simple stereo beam forming allowed the separation of each biosonar sound source, which allowed us to count the number of vocalizing porpoises. We acoustically detected 204 porpoises from one vessel and 199 from the other vessel. In comparison, we visually detected 163 porpoises from one vessel and 162 porpoises from the other. The visual observations matched the acoustic detections well, except for cases of isolated individuals. The calculated detection probability of acoustic detection was approximately twice that for visual detection for each vessel. We calculated the probability of detecting porpoises in a strip width of 300 m as 0.46 from the acoustic surveys and 0.19 from the visual surveys. Ninety-four single porpoises were detected acoustically compared with 24 detected visually from one vessel, and the observations from the other vessel were similar. This difference in detection probabilities between acoustics and visual methodologies was caused by the large number of single individuals that were missed by visual observers. However, the sizes of large groups were underestimated using the acoustic methods because of the limited resolution of the bearing angle imposed by the short system baseline. The detection probability of finless porpoises in the Yangtze River was strongly influenced by group size. Acoustic and visual observations complemented each other in the estimation of the accurate abundance of finless porpoises. The use of simple, relatively inexpensive acoustic monitoring systems will enhance population surveys of free-ranging, echolocating odontocetes.

Simple and relatively inexpensive acoustic logging systems such as the one we used in this survey of finless porpoises in the Yangtze River should enhance population surveys of cetaceans that vocalize often and travel in relatively small groups. The passive acoustic survey system

was highly effective for detecting solitary porpoises, which are hard to detect otherwise by visual methods, though it did not work as well for counting porpoises in large groups. Consequently, combining stereo passive acoustic methods with traditional visual observation methods will provide more accurate estimates of the population of dolphins and porpoises.

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