Acoustic characteristics of biosonar sounds of free-ranging botos (*Inia geoffrensis*) and tucuxis (*Sotalia fluviatilis*) in the Negro River, Amazon, Brazil

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Odontoceti emit broadband high-frequency clicks on echolocation for orientation or prey detection. In the Amazon Basin, two odontoceti species, boto (Amazon River dolphin, *Inia geoffrensis*) and tucuxi (*Sotalia fluviatilis*), live sympatrically. The acoustic characteristics of the echolocation clicks of free-ranging botos and tucuxis were measured with a hydrophone array consisting of a full-band and an acoustic event recorder (A-tag). The clicks of the two species were short-duration broadband signals. The apparent source level was 201 dB 1 μPa peak-to-peak at 1 m in the botos and 181 dB 1 μPa peak-to-peak at 1 m in the tucuxis, and the centroid frequency was 82.3 kHz in the botos and 93.1 kHz in the tucuxis. The high apparent source level and low centroid frequency are possibly due to the difference in body size or sound production organs, especially the nasal structure, the sound source of clicks in odontoceti. © 2015 Acoustical Society of America.

[JFL] Pages: 687–693

I. INTRODUCTION

Odontoceti emit broadband high-frequency clicks on echolocation for orientation or prey detection (Au, 1993). The acoustic characteristics of the echolocation clicks play a key role in their biosonar performance and also provide valuable information for passive acoustic monitoring (PAM), a useful tool to observe the presence and movement of odontoceti for conservation purposes (Mellinger, 2007).

In the Amazon Basin, two odontoceti species, boto (Amazon River dolphin, *Inia geoffrensis*) and tucuxi (*Sotalia fluviatilis*), live sympatrically (Best and da Silva, 1993; Vidal et al., 1997; Martin and da Silva, 2004; Martine et al., 2004; Gomez-Salazar et al., 2012). Botos have a mean body length of 231.5 cm in the male and 199.8 cm in the female, and a mean weight of 154.2 kg in the male and 99.6 kg in the female (da Silva and Best, 1996; Martin and da Silva, 2006). Botos inhabit the main river of the Amazon River, as well as the narrow channels or the flooded forests (Martin and da Silva, 2004; Martin et al., 2004). Tucuxi have a maximum body length of 132 cm and maximum weight of 55 kg (Flores and da Silva, 2009). They inhabit only the main stream of the river with high-speed current and deep water, and are not found inside the narrow channels or flooded forests (Martin et al., 2004). Both species in the Amazon River, boto and tucuxi, have been reported to produce broadband sonar signals (Kamminga et al., 1993). However, there is currently no detailed information on the acoustic characteristics of these echolocation signals in botos and tucuxis, especially the apparent source level (Møhl et al., 2000), for which a basic description of the waveform and frequency has been published (Kamminga et al., 1993).

Our study is the first to present the detailed acoustic characteristics of the echolocation signals from free-ranging botos and tucuxis. The echolocation clicks were recorded using a hydrophone array consisting of a full-band recorder and acoustic event recorder (A-tag) simultaneously. We discuss the differences in acoustic characteristics between the two species.
II. MATERIALS AND METHODS

A. Study site and period

The study site was a small channel near a resort hotel, Ariau Amazon Towers, located in the Negro River, Amazonas State, Brazil (03°04′22.4 S, 060°27′29.2 W). The width of the channel was ~50 m. The observation was conducted from January 21 to 30, 2011. The group of botos in this study site existed in free-ranging conditions without confinement in an enclosure and had been fed by hotel staff since 2005 (de Sá Alves et al., 2011). More than 25 individuals were identified at the site by the staff. The feedings and dolphin swimming activities with tourists were conducted four times per week, on Tuesdays, Thursdays, Saturdays, and Sundays. The number of tourists allowed to swim with the botos was restricted to five at any one time.

B. Visual observation

Visual observation was conducted in a small channel (50 m in width) by one observer sitting in a position just above the broadband hydrophone placed between two A-tags (Fig. 1). The narrow channel enabled easy species identification of the observed animals. The recorded sounds were used for analysis when a dolphin surfaced for breath in the observable area within 45°∼135° of the hydrophone, where 0° corresponds to a line perpendicular to the riverbank. For each effective encounter, the time of observation, and distance and direction from the hydrophone (in meters and degrees) were recorded. The visual observers were informed of reference distances of several points on the other side of the channel measured in advance using a laser range finder (Laser1200S, Nikon Corporation, Tokyo, Japan). A large protractor was placed in front of the observer for measurement of the direction to the animal at a resolution of 5°. The time of observation was recorded on the second time scale on a recording sheet referring to a watch synchronized to the local standard time (UT-4 h). The clocks of all the acoustic devices were also synchronized to the local standard time, using the time of a personal computer as the initial reference time.

C. Recording system

We employed a broadband and an acoustic event recorder (A-tag) for recording the echolocation clicks. To record the echolocation sounds, a hydrophone (SH-200 k, −211 dB/V ± 3 dB, System Intech Co. Ltd., Tokyo, Japan), stereo amplifier (Aquafeeler, Bandpass 0–200 kHz, Gain 60 dB, System Intech Co. Ltd., Tokyo, Japan) and a digital hard-disc recorder (EZ0751, sampling rate 500 kHz, maximum input range 2 V, resolution 16 bit, NF Inc., Yokohama, Japan) were used.

The A-tag (Marine Micro Technology, Saitama, Japan) is an ultrasonic pulse event recorder that records the sound pressure, the absolute time of the sound detection and the sound source direction of pulses encoded in the arrival time difference between two hydrophones. The A-tag consists of two hydrophones, a passive band-pass filter (55–235 kHz), CPU, flash memory (128 MB), and batteries [lithium battery (CR2) or UM-1 alkaline battery]. The two hydrophones (HP1 and HP2) have different maximum-sensitivity frequencies (130 and 70 kHz, respectively). The intensity and the arrival time difference of the high-frequency pulse sounds were recorded every 2 ms when the received sound pressure level was greater than the preset threshold of 129 dB re 1 μPa peak-to-peak (p-p), but no data were stored when the received sound pressure level was lower than the preset threshold. For measurement of the sound arrival time difference, an independent high-speed counter started when a sound triggered either the first or second hydrophone and continued counting until the other hydrophone was triggered. The sampling interval of the high-speed counter was 1.084 μs. The relative angle of the sound source from the A-tag was calculated from the sound arrival time difference between the two hydrophones and the length of the baseline between the two hydrophones (Akamatsu et al., 2005).

Two A-tags were fixed vertically 10 m apart at a depth of 50 cm. A floating house facing the channel was used as the observation platform (Fig. 1). A broadband hydrophone was set equidistant between the two A-tags at the same depth. The river width was 70 m, the floating house was 20 m from the riverbank, and the water depth at the monitoring site was 4 m.

D. Signal analysis

The recording period of the sounds was divided into the following three categories based on the visual observation records: only botos; only tucuxis; and mixed species. The recording period of only botos or only tucuxis was defined as a period in which only botos or only tucuxis were observed visually for a period of more than 5 min. The recording period of the mixed group was defined as that in which both species were observed within a period of 5 min. For analyzing the acoustic characteristics of the echolocation clicks of each species, we used the broadband data recorded during the periods with only botos and only tucuxis.

The echolocation clicks of odontoceti are highly directional. The frequency characteristics and source level of the off-axis clicks differ from those of the on-axis clicks (Au, 1993). Thus, it is necessary to select the on-axis clicks to

FIG. 1. Schematic drawing of the field site. Two A-tags and a broadband hydrophone were placed at 50-cm depth by attachment to the wooden poles of a platform floating in the river. The broadband hydrophone was placed equidistant between the two A-tags. R denotes the distance from the hydrophone to the sound source.
analyze the acoustic characteristics (Au 1993; Mellinger, 2007). However, it is difficult to identify the on-axis clicks recorded in natural conditions where the animals are swimming in turbid waters. Following Kyhn et al. (2009), we used the following set of criteria for selecting the possible on-axis clicks: (i) recorded on all five channels (one broadband hydrophone and two A-tags with four hydrophones); (ii) occurring in a series of clicks closely spaced in time, normally first increasing then decreasing in amplitude; (iii) the direct path of the click was stronger than any surface or bottom reflections; (iv) the signal to noise ratio was larger than 10 dB; (v) the click was maximum amplitude in the scan. For selecting the possible on-axis clicks, we used the waveform visualization software associated with the EZ0751 (NF Inc., Yokohama, Japan).

For each selected click, the acoustic characteristics of the sound source were calculated with a custom-written algorithm using Igor pro 6.1.2.1 (WaveMetrics Inc., Lake Oswego, OR). We employed the calculated values from Madson and Wahlberg (2007) and Morisaka et al. (2011).

The click duration at 10 dB was defined as the duration of the click envelope within 10 dB below the peak intensity.

The power spectrum of the signals was calculated using a 256-point fast Fourier transform (FFT) size and Hanning window. The peak frequency (f_p, kHz) represented the frequency at the highest spectrum energy. The centroid frequency (f_0, kHz) represented the frequency that divided the power spectrum into two halves of equal energy. Three types of bandwidth (BW) were defined, as follows: the −3 dB BW (kHz) covered the frequency range within 3 dB below the maximum spectral peak; the −10 dB BW (kHz) covered the frequency range within 10 dB below the maximum spectral peak; and the root-mean square BW (rms_BW) represented the spectral standard deviation around the centroid frequency of the linear spectrum. The quality factor (Q_rms) was the value of the centroid frequency divided by the rms_BW. For details of the equations for each parameter, see Au (1993) and Madsen and Wahlberg (2007).

E. Apparent source level

The apparent source level (ASL, dB re 1 µPa) is defined as the sound pressure back-calculated to 1 m in an unknown aspect to the animal (Mohl et al., 2000), and is calculated using the following equation:

\[
\text{ASL} = \text{RL} + \text{TL} = \text{RL} + 20 \log R + zR,
\]

where RL is the received level. The RLs were obtained from the peak-to-peak sound pressure level. The transmission loss (TL) was calculated assuming spherical sound propagation and frequency-dependent absorption using an absorption coefficient, \( \alpha \), of 0.025 dB m\(^{-2}\) at 90 kHz (close to the centroid frequency of the clicks of botos and tucuxis). R represents the distance from the sound source to the hydrophone (Fig. 1), which was calculated by triangulation using two bearing angles measured acoustically by A-tags (details described in Li et al., 2009). The energy flux density was the signal energy integrated within the 10 dB BW (dB re 1 µPa\(^2\)). Analysis of the apparent source level was conducted using Igor pro 6.1.2.1 (WaveMetrics Inc., Portland, OR).

F. Statistical analysis

We conducted the Mann–Whitney U test to compare the acoustic differences between botos and tucuxis in the following parameters: apparent source level, energy flux density, duration, peak frequency, centroid frequency, rms BW, Q value, −3 dB BW, and −10 dB BW. For estimating the effective acoustic range by A-tag, the detection ranges by A-tag (R) and the detection ranges by visual observation were compared using Mann–Whitney U test. All statistical analyses were carried out in Igor pro 6.1.2.1 (WaveMetrics Inc., Portland, OR).

III. RESULTS

Over the 10-day study period, broadband recording was conducted for a total of 7 h 44 min. The total number of sightings was 1168 for the botos, and 314 for the tucuxis. The total duration of the observation time for only botos was ~9 h, for only tucuxi 1.3 h, and for the mixed species group the time was ~3 h. The acoustic event recorder A-tags were deployed for 104 h in total, including the time during which no visual observation was conducted. The mean detection range by visual observation was 37.3 m (SD = 23.8, min = 3, max = 200) for the botos and 33.8 m (SD = 28.4, min = 5, max = 200) for the tucuxis.

The number of possible on-axis clicks selected using the criteria described above was 75 for the botos and 56 for the tucuxis. Figure 2 shows the typical waveforms of clicks from botos and tucuxis. The acoustic parameters of each sound source are summarized in Table I. The mean apparent source level of the botos (201 dB re 1 µPa at 1 m) was larger than that of the tucuxis (181 dB re 1 µPa at 1 m) (Mann–Whitney U test, \( p < 0.01 \)). The peak frequency (f_p) and centroid frequency (f_0) of the tucuxis (82.3 and 94.4 kHz, respectively) were lower than those of the tucuxis (93.1 and 99.2 kHz, respectively) (Mann–Whitney U test, \( p < 0.05 \)). The Q value (2.7 in the botos and 2.8 in the tucuxis) showed that the clicks of both species were of broadband type. The mean detection range by A-tag of the botos (135.6 m) was longer than that of the tucuxis (57.9 m) (Mann–Whitney U test, \( p < 0.01 \)).

Figure 3 shows the histogram of the click parameters. The distribution of the peak frequency of the tucuxis displayed a bimodal pattern, whereas that of the botos displayed no clear multiple distribution peaks. The centroid frequency and rms bandwidth displayed a unimodal pattern in both the botos and tucuxis.

IV. DISCUSSION

The echolocation clicks of the botos and tucuxis recorded in this study (boto: duration = 17.3 µs; \( Q = 2.7 \); tucuxi: duration = 16.5 µs; \( Q = 2.8 \)) were both short-duration broadband signals, similar to other previously reported odontoceti. The short-duration broadband signals reported in the several different delphins included tucuxis (Table II):
bottlenose dolphin (*Tursiops truncatus*); duration = 21 μs,  
$Q = 2.8$ (Wahlberg *et al.*, 2011); Indo-Pacific bottlenose dol-
phin (*Tursiops aduncus*); duration = 18 μs,  
$Q = 2.3$ (Wahlberg *et al.*, 2011); and Pigmy killer whale (*Feresa attenuata*); duration = 20–40 μs,  
$Q = 2–3$ (Madsen *et al.*, 2004b). Kamminga *et al.* (1993) also demonstrated the 
short-duration signal of botos and tucuxis (duration 25–50 μs 
for both botos and tucuxis). In our study, the differences in 
several parameters between the botos and tucuxis suggested 
that these two species may emit different echolocation 

The mean apparent source levels were 201 dB re 
$1 \mu Pa_{pp}$ at 1 m in the botos and 181 dB re $1 \mu Pa_{pp}$ at 1 m in 
the tucuxis. The source level of the clicks is possibly 
affected by the body size in odontoceti. Considering the 
maximum body size of adult botos (2.55 m, Martin and da 
Silva, 2004; da Silva 2009), the apparent source level was 
similar to that of other spices of similar or larger size: bottle-
nose dolphin (Table II); body size = 2.5–3.8 m (Mead and 
Potter, 1990; Read *et al.*, 1993); ASL = 199 dB re $1 \mu Pa_{pp}$ 
at 1 m (Wahlberg *et al.*, 2011); Indo-Pacific bottlenose 
dolphin; body size = 2.7 m (Wang and Yang, 2009);

**TABLE I.** Average (± standard deviation) and range of echolocation click source parameters produced by botos and tucuxis.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Boto (<em>Inia geoffrensis</em>)</th>
<th>Tucuxis (<em>Sotalia fluviatilis</em>)</th>
<th>Mann–Whitney U test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of analyzed clicks</td>
<td>Mean value (SD)</td>
<td>Range</td>
<td>Mean value (SD)</td>
</tr>
<tr>
<td>Apparent source level (dB re 1 mPa$_{pp}$ at 1 m)</td>
<td>201.8 (±12.3)</td>
<td>189.7–228.7</td>
<td>181 (±11.5)</td>
</tr>
<tr>
<td>Energy flux density (dB re 1 mPa$^2$ at 1 m)</td>
<td>94.2 (±3.1)</td>
<td>87.3–98.1</td>
<td>90.5 (±4.5)</td>
</tr>
<tr>
<td>Duration (μs)</td>
<td>17.3 (±6.7)</td>
<td>7.9–36.3</td>
<td>16.5 (±5.9)</td>
</tr>
<tr>
<td>Peak frequency (kHz)</td>
<td>82.3 (±20.8)</td>
<td>46.9–125.0</td>
<td>93.1 (±31.9)</td>
</tr>
<tr>
<td>Centroid frequency (kHz)</td>
<td>94.4 (±15.6)</td>
<td>55.2–125.6</td>
<td>99.2 (±23.1)</td>
</tr>
<tr>
<td>rms BW (kHz)</td>
<td>36.5 (±8.3)</td>
<td>21.5–51.2</td>
<td>35.3 (±6.8)</td>
</tr>
<tr>
<td>$Q$ value (kHz)</td>
<td>2.7 (±0.6)</td>
<td>1.9–4.4</td>
<td>2.8 (±0.6)</td>
</tr>
<tr>
<td>−3 dB BW (kHz)</td>
<td>40.0 (±14.9)</td>
<td>18.1–70.8</td>
<td>21.5 (±10.4)</td>
</tr>
<tr>
<td>−10 dB BW (kHz)</td>
<td>93.2 (±35.6)</td>
<td>40.7–158.2</td>
<td>70.9 (±29.2)</td>
</tr>
<tr>
<td>Detection range by A-tag (m)</td>
<td>135.6 (±98.3)</td>
<td>58.2–394.9</td>
<td>57.9 (±43.2)</td>
</tr>
<tr>
<td>Detection range by visual observation (m)</td>
<td>37.3 (±23.8)</td>
<td>3–200</td>
<td>33.8 (±28.4)</td>
</tr>
</tbody>
</table>
ASL = 205 dB re 1 μPa p-p at 1 m (Wahlberg et al., 2011); Indo-Pacific humpback dolphin (Sousa chinensis); body size = 2.5 m (Jefferson et al., 2012); ASL = 181.7 dB re 1 μPa p-p at 1 m (Kimura et al., 2014); false killer whale (Pseudorca crassidens); body size = 6 m (Baird, 2009a); ASL = 220 dB re 1 μPa p-p at 1 m (Madsen et al., 2004a); Risso’s dolphin (Grampus griseus); body size = 4 m (Baird, 2009b); 220 dB re 1 μPa p-p at 1 m (Madsen et al., 2004a); and Pigmy killer whale; body size = 2.31 m (Donahue and Perryman, 2009); 197/223 dB re 1 μPa p-p at 1 m (Madsen et al., 2004b).

The apparent source level of the tucuxis was also consistent with other species with similar body size; Harbour porpoise (Phocoena phocoena); body size = 1.2 m (Bjorge and Tolley, 2009); ASL = 191 dB re 1 μPa p-p at 1 m (Villadsgaard et al., 2007); and Heaviside’s dolphin (Cephalorhynchus heavisidii); body size = 1.7 m (Dawson, 2009); 173 dB re 1 μPa p-p at 1 m (Morisaka et al., 2011).

The \( f_p \) and \( f_0 \) were 82.3 and 94.4 kHz, respectively, in the botos, and 93.1 and 99.2 kHz, respectively, in the tucuxis. These results were consistent with Kamminga et al. (1993), who reported that the ranges of dominant frequency of the clicks of wild botos and tucuxis were 85–100 kHz in botos and 80–95 kHz in tucuxis, although they did not examine the frequency spectrum of the clicks. The peak centroid frequencies of the botos and tucuxis were similar or slightly higher than the broadband signals emitted by other delphinids: bottlenose dolphin (Table II); \( f_0 = 80 \) kHz; Indo-Pacific bottlenose dolphin; \( f_0 = 91 \) kHz (Wahlberg et al., 2011).
false killer whale; $f_0 = 75$ kHz; $f_p = 49$ kHz; Risso’s dolphin; $f_0 = 49$ kHz; $f_p = 40$ kHz (Madsen et al., 2004a); and Pigmy killer whale; $f_0 = 45–117$ kHz; $f_0 = 70–85$ kHz (Madsen et al., 2004b).

The $f_p$ and $f_0$ of the tucuxis were slightly higher than those of the boto. Cranford (2000) postulated that the differences in the characteristics of the clicks might be caused by the differences in the sound production organs, especially the nasal structure. The size of the monkey lips/dorsal bursae (MLDB) complex inside the nasal region, which is the sound source of clicks in odontoceti, is possibly related to the body size in the two species. The lower peak and centroid frequencies in botos are consistent with this hypothesis. In tucuxis, the histogram of the peak frequency displayed a bimodal distribution. A possible explanation for this distribution is that tucuxis emit two types of click with different frequency spectra. Small odontoceti create the click sounds using two pair structures known as the MLDB complex inside the nasal region (Cranford et al., 1996). Clicks with different frequency spectra produced by an odontoceti were generated independently by two different MLDB complexes (Cranford, 2000). False killer whales, which can emit four types of click with different frequency spectra, were also hypothesized to use different sound production sources (Au et al., 1995).

Although we have no information regarding the MLDB complex of tucuxis, the bimodal distribution of the peak frequency of their clicks may be derived independently from two different MLDB.

Another possible explanation for the difference in sound characteristics is a difference in the sensing tactics, as discussed by Kyhn et al. (2009). Under the complex conditions in flooded forests, with trunks, branches and floating vegetation, in the narrow channel there would be more clutters and reverberations than the main channel. The source level might be lower in the complex conditions to avoid intense clutter of the reverberation. Lower frequency sounds travel further with less distortion in conditions that promote reverberation.

Data from previous studies in part support this hypothesis as the peak frequency of botos inhabiting flood forest was slightly lower than that of tucuxis living in open water. However, botos emit larger source-level clicks than tucuxis, which prefer open water, such as a main river (Martin and da Silva, 2004; Martin et al., 2004).

The mean detection range by A-tag of the boto was greater than that of the tucuxis, and the minimum detection range by A-tag of the boto was 58.2 m, whereas it was 8.5 m in the tucuxis. However, there was no difference between the detection ranges of the two species by visual observation. These results suggested that the beam pattern of botos could be narrower than that of tucuxis because the analyzed clicks should be received by all five channels of the monitoring array. Although to date no research has been conducted on the beam directionality in botos and tucuxis, these results are consistent with the sharply directional beam observed in botos. The Ganges river dolphin has fairly narrow beam directionality (Ura et al., 2007; Bahl et al., 2007).

Although the Ganges river dolphin and boto are phylogenetically separate (Nikaido et al., 2001), the sharp beam pattern could provide higher spatial resolution in shallow waters comprising a complex environment.

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