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Ultrasound use by Sunda colugos offers new insights into the communication of these cryptic mammals

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ABSTRACT

Recent reports of the use of ultrasound for communication by nocturnal mammals have expanded our understanding of behaviour in these animals. The vocal repertoire of colugos has so far only been known to include audible sound. Here, we report the use of ultrasound calls by Sunda colugos (*Galeopterus variegatus,* order Dermoptera). We recorded one type of call emitted by seven individuals with mean individual frequencies between 37.4 ± 0.6 and 39.2 ± 0.7 kHz during its maximum energy and lasting 28.7 ± 1.6 to 46.9 ± 21.1 ms. Each call showed 3–36 sequential pulses with individual mean interpulse intervals between 423.0 ± 101.4 and 1230.0 ± 315.4 ms. High frequency calls may serve as cryptic anti-predator alarm calls. Our observations suggest that more species of nocturnal mammals may use ultrasound to communicate, and that further studies are needed to determine the occurrence, function and diversity of these calls.

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Introduction

Many nocturnal animal species use ultrasound. The best-known examples are insect-eating bats that use ultrasound to echolocate their prey and avoid obstacles during high-speed flight (Jacobs and Bastian 2016). Rodents are also known to communicate with ultrasound (Nyby and Whitney 1978; Thomas and Barfield 1985; Dempster and Perrin 1991; Ancillotto et al. 2014) and to respond to cold ambient temperature by emitting ultrasound (Smith 1972; Blake 1992). Some other mammals, including dogs, and most insects can also hear ultrasonic calls (Sales and Pye 1974). However, little is known about the use of ultrasound in communication by small arboreal nocturnal mammals. Tarsiers (Tarsiidae) are the only primates known to hear ultrasonic components up to 91 kHz and can communicate at a frequency of 70 kHz (Stanger 1995; Ramsier et al. 2012). Ramsier et al. (2012) suggested that ultrasound may be used to avoid detection by predators. Most nocturnal primates emit calls with ultrasonic components (Zimmerman 1981; Stanger 1995; Zimmermann 1995;

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Braune et al. 2008), while their hearing seems to be limited at 65 kHz (Zimmerman 1981; Coleman and Boyer 2012).

Colugos (order Dermoptera) are little-studied nocturnal, arboreal, gliding mammals and are a sister clade to primates (Janečka et al. 2007; Mason et al. 2016). Colugos are the most accomplished gliders among all mammals, with a fur-covered gliding membrane (patagium) that extends between their head and forelimbs, between fore- and hindlimbs, and between hindlimbs and tail (Panyitina et al. 2015) and allows them to glide up to 136 metres (Lim 2007). Colugos feed mainly on leaves, and occasionally on fruits and flowers (Lim 2007). Little is known about the social behaviour of colugos and they are usually thought to be solitary or form loose groups of few individuals (Lim 2007).

The IUCN recognizes two species (*Galeopterus variegatus* and *Cynocepahus volans*), which are listed as Least Concern, but colugos depend on intact forests and connected canopies due to their gliding behaviour, so they may be threatened by forest loss and degradation (Feldhamer et al. 2007; Janečka et al. 2008). Due to their morphological, phylogenetic and ecological uniqueness, colugos should be a conservation priority within their distribution range of Sundaland (Janečka et al. 2008; Mason et al. 2016). Populations from Borneo, Sumatra and Peninsula Malaysia are genetically and morphologically different and some researchers have suggested that colugos may include four to eight different species (Janečka et al. 2008; Mason et al. 2016).

Colugos are rather quiet and emit limited numbers of audible calls (Dzulhelmi and Abdullah 2009a). In Sarawak, Malaysia, they produce at least four distinct types of calls in the audible range, which have been described as *greeting call*, *disturbed call*, *calling* and *courtship call* (Dzulhelmi and Abdullah 2009a), but their communication system is not well understood. Here, we describe the first records of ultrasound use by colugos, based on our observations of Sunda colugos (*G. variegatus*) in Peninsular Malaysia.

Methods

During a bat survey walk on 19 October 2017 (dry weather with clear sky), on the main trail of The Habitat Penang Hill (Bukit Bendera; 5°25′28.81″N 100°15′3.53″E, 833 m asl, Pulau Pinang, Malaysia), we used a directional Pettersson M500 USB ultrasound microphone connected to a tablet to record an ultrasound call at 8:25 pm from a location about 10–15 metres away at canopy level. This call had characteristics very different from bat ultrasound. Ultrasound calls of bats usually show a constant frequency or frequency-modulated components (Fenton et al. 1999). However, the frequencies of the extraordinary call that we recorded formed a 'wavy' pattern (Figure 1). On the subsequent night, to identify the caller, we conducted another night walk, recording ultrasound from the surroundings using the same ultrasound microphone while also using a thermal image camera (FLIR Scout640) to identify nocturnal mammals. When we detected an unidentified ultrasound call, we searched the area using the thermal device, targeting tree trunks and the canopies of nearby trees in the direction from which the ultrasound was produced. After detecting a thermal signature, we used a red-light head torch to identify the animal emitting the calls. When the calling animal was spotted, we recorded the location and time. To verify the source of the calls, we then repeatedly moved the ultrasound microphone towards and away from the animal to verify that the volume of the calls varied proportionally with the distance between the microphone and the animal. We analysed the calls using BatSound

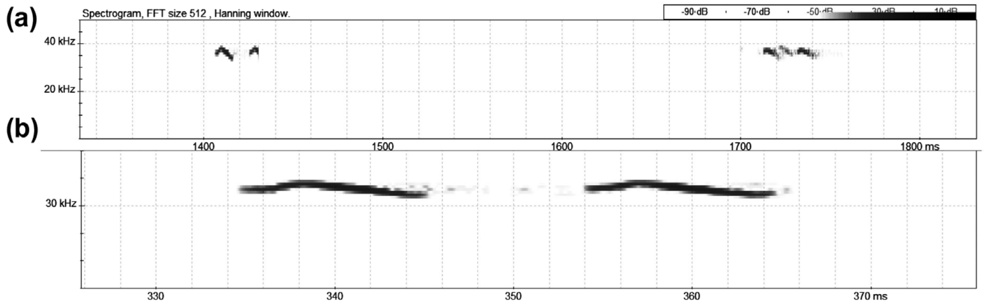

Figure 1. Recordings of colugo sequential calls by one individual: (a) Zoom in from the 1400th to 1800th ms to show the interval between calls; (b) Zoom in on the first call to show its spectral characteristics.

Table 1. Environmental parameters during seven direct colugo sightings; 20 October 2017 to 05 November 2017; Penang Malaysia.

Number of sighting	Date of the sighting	Relative humidity [%]	Distance of the observer from the tree [m]	Height of the animal in the tree [m] above ground	Distance of the observer from the animal [m][a]
1	20 October 2017	79	7	13	14.8
2	20 October 2017	79	10	15	18.0
3	20 October 2017	79	3	9	9.5
4	31 October 2017	82	7	12	13.9
5	5 November 2017	87	10	18	20.6
6	5 November 2017	87	7	10	12.2
7	5 November 2017	87	2	6	6.3

[a]All angles are 90 degrees as we calculated perpendicular distance from the observer to the tree and the height of the animals on the tree.

4 (Pettersson Elektronik AB; http://www.batsound.com) to determine the call frequency with maximum energy and the duration of each call.

Results

Each time we detected the unusual ultrasound pattern, we observed a Sunda colugo in the immediate environment within a distance of 20 m and confirmed that the call volume varied with distance to the colugo (Table 1). Once, a colugo glided from one side of the forest trail to the other side (ca. 10 m) and we recorded ultrasound calls from each location before and after the animal moved.

We recorded nine additional sequential calls (i.e. calls were emitted continuously in constant intervals by one individual at one time) during three colugo sightings on 20 October 2017 and two sequential calls on 23 October 2017 (no sighting) along a forest trail within the Penang Hill Permanent Forest Reserve. We then repeated the survey in Penang Botanic Gardens (Taman Kebun Bunga, 05°26′15.7200″N, 100°17′26.5200″E, 60 m asl), to confirm our findings in a different location. We recorded a total of five sequential calls during four direct individual sightings in the Penang Botanic Gardens on 31 October and 5 November 2017.

In total, we recorded colugo ultrasound sequential calls 16 times and sighted seven individuals that emitted ultrasound calls (Table 2). The sonograms of these calls normally demonstrated wavy patterns of two peaks, and occasionally one or three peaks. The

Table 2. Ultrasound calls recorded during seven direct colugo sightings; 20 October 2017 to 05 November 2017; Penang Malaysia.

Number of sighting	Date of the sighting	Time individual was first sighted	Number of pulses emitted by the sighted individual	Number of wavy peaks per pulse	Mean call parameters							
					$FMax_E$ [a] [kHz]	D[b] [ms]	IPI[c] [ms]	SF[d] [kHz]	EF[e] [kHz]	HF[f] [kHz]	LF[g] [kHz]	BW[h] [kHz]
1	20 October 2017	21:50	7	2	37.6 ± 0.8	35.0 ± 2.0	1230.0 ± 315.4	37.3 ± 0.5	35.6 ± 1.1	40.6 ± 0.8	33.3 ± 1.1	7.3 ± 1.5
2	20 October 2017	22:13	36	1–3	37.4 ± 0.6	37.3 ± 14.1	560.0 ± 446.1	36.5 ± 1.5	35.4 ± 1.2	39.9 ± 2.5	31.2 ± 2.6	8.8 ± 4.7
3	20 October 2017	22:52	8	2	37.7 ± 0.5	43.4 ± 5.7	965.2 ± 223.7	37.6 ± 0.7	35.5 ± 1.4	38.0 ± 0.0	32.4 ± 4.2	5.6 ± 4.2
4	31 October 2017	20:29	4	2	37.7 ± 0.1	28.8 ± 1.5	423.0 ± 101.4	37.3 ± 0.5	35.8 ± 1.0	39.3 ± 0.5	33.8 ± 0.5	5.5 ± 1.0
5	5 November 2017	19:30	22	1–2	39.2 ± 0.7	38.5 ± 6.9	524.5 ± 236.4	39.7 ± 1.3	37.7 ± 0.8	41.0 ± 0.5	34.7 ± 1.2	6.4 ± 1.3
6	5 November 2017	19:38	3	2	37.8 ± 0.1	28.7 ± 1.5	792.0 (n = 1)	37.0 ± 0.0	34.7 ± 0.6	38.7 ± 0.6	34.3 ± 0.6	4.3 ± 1.2
7	5 November 2017	20:00	8	2	38.1 ± 0.4	46.9 ± 21.1	424.7 ± 15.0	37.8 ± 0.8	35.5 ± 0.8	39.7 ± 0.5	34.8 ± 0.4	4.8 ± 0.4

[a]Frequency at maximum energy.
[b]Duration.
[c]Interpulse interval.
[d]Start frequency.
[e]End frequency.
[f]Highest frequency.
[g]Lowest frequency.
[h]Bandwidth.

mean start frequency of the calls was 37.5 ± 1.7 kHz and the mean ending frequency was 36.0 ± 1.4 kHz. The call frequencies had a mean maximum energy at 37.9 ± 0.9 kHz (numbers of sightings = 7) within a mean bandwidth of 7.1 ± 3.5 kHz and a mean duration of 37.9 ± 11.4 ms (Figure 1).

Discussion

Our findings provide new insights into the communication of nocturnal mammals in South-East Asia. Like bats, several nocturnal members of the Primatomorpha clade, including tarsiers, slow lorises, galagos and colugos, produce ultrasound, apparently for communication (Zimmerman 1981; Ramsier et al. 2012). The ultrasound calls emitted by Sunda colugos had frequency variation in a 'wavy' pattern with one to three peaks for each pulse. This call structure is distinguished from the ultrasounds call characteristics of bats, which are frequency modulated (straight lines or curves on the spectrograms), at a constant frequency, or the combination of both (Mancina et al. 2012). The unique call morphology of colugos also differs from the spectral properties of the ultrasonic calls of other nocturnal mammals, such as mouse lemurs (which are multiple harmonics, highly frequency-modulated with smears; Braune et al. 2008), rodents (which are at a constant frequency or complicated frequency-modulated; Roberts 1975; Brudzynski and Fletcher 2010), and tarsiers (which are slightly curved with a dominant frequency at 70 kHz; Ramsier et al. 2012).

The fossil record suggests that early mammals were small and nocturnal insectivores living on trees (Gerkema et al. 2013). Selection for cryptic communication at night may have favoured the parallel evolution of ultrasound communication in multiple lineages of nocturnal mammals if common predators were unable to hear ultrasound vocalizations (Gerkema et al. 2013).

Ear structures of mammals are evolved to be closely adapted to the sounds that the animals emit (Coleman and Boyer 2012). The basilar membrane length and number of cochlear turns of bats were found to be positively correlated to their echolocation call frequencies (Davies et al. 2013) and the same pattern appears for primate species (Coleman and Boyer 2012). Euarchontan taxa generally have relatively short cochleae but ultrasound hearing tarsiers have exceptionally long cochleae (20.1– 24.1 mm; Coleman and Boyer 2012) despite their small body mass (below 150 g). The colugo has a cochlear length between 20.50 and 22.86 mm with a window oval area of 0.81–1.08 mm^2 (Coleman and Boyer 2012). Their cochlear labyrinth volume is 11.6 mm^3 with a body mass of up to 2 kg (Armstrong et al. 2011). The cochlear volume of colugos is typical for a mammal of their size and similar to that of slow lorises (Coleman and Boyer 2012). Kirk and Gosselin-Ildari (2009) suggested that, as the volume of the cochlear labyrinth increases, there is a negative correlation with highest and lowest audible frequencies.

Ultrasound calls in colugos should be further studied in their ecological context to clarify the functions of these calls. Our preliminary observations suggest that the calls may have been alarm calls produced in response to our presence, but this inference needs to be further tested. Alternatively, these calls may function as sexual signals, contact calls, or territorial vocalizations. Unlike bats, colugos are not capable of true flight. Their night vision is excellent, and their diet is mainly plant-based (Dzulhelmi and Abdullah 2009b) Thus, we assume that colugos do not use echolocation. Accordingly, we did not detect ultrasound use by colugos while gliding (one observation) or feeding (three observations).

Visual surveys of small nocturnal mammals are labour intensive and disturb the natural behaviour of the animal. Our observations suggest that if individuals can be identified using unique call characteristics, passive acoustic monitoring may be an efficient method to estimate colugo population densities and obtain information about their ranging behaviour. Further studies are needed to better understand the ecology and behaviour of these cryptic animals.

Data accessibility

Audio files supporting this article have been uploaded as supplementary material.

Ethics

All procedures were approved by and adhered to institutional and national guidelines.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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