Vocalizations of wild Asian elephants (*Elephas maximus*): Structural classification and social context

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Elephants use vocalizations for both long and short distance communication. Whereas the acoustic repertoire of the African elephant (*Loxodonta africana*) has been extensively studied in its savannah habitat, very little is known about the structure and social context of the vocalizations of the Asian elephant (*Elephas maximus*), which is mostly found in forests. In this study, the vocal repertoire of wild Asian elephants in southern India was examined. The calls could be classified into four mutually exclusive categories, namely, trumpets, chirps, roars, and rumbles, based on quantitative analyses of their spectral and temporal features. One of the call types, the rumble, exhibited high structural diversity, particularly in the direction and extent of frequency modulation of calls. Juveniles produced three of the four call types, including trumpets, roars, and rumbles, in the context of play and distress. Adults produced trumpets and roars in the context of disturbance, aggression, and play. Chirps were typically produced in situations of confusion and alarm. Rumbles were used for contact calling within and among herds, by matriarchs to assemble the herd, in close-range social interactions, and during disturbance and aggression. Spectral and temporal features of the four call types were similar between Asian and African elephants.
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I. INTRODUCTION

A number of mammalian groups, including carnivores, ungulates, cetaceans, rodents, and primates, use acoustic signals for intraspecific communication in a variety of contexts such as mate-finding, courtship, aggression, alarm, and territoriality (Bradbury and Vehrencamp, 1998). Elephants, which are the largest terrestrial mammals, also use acoustic signals to communicate over both short-medium (Douglas-Hamilton, 1972; Krishnan, 1972; McKay, 1973; Poole and Moss, 1989; Poole *et al.*, 1988; McComb *et al.*, 2003) and long distances (Garstang *et al.*, 1995; Larom *et al.*, 1997). Whereas acoustic signaling in the African elephant (*Loxodonta africana*) has been extensively studied in their savannah habitats (Poole and Moss, 1989; Payne, 1998; Poole *et al.*, 1988; Poole, 1999; Langbauer, 2000), very little is known about acoustic signaling in Asian elephants (*Elephas maximus*), which are largely forest dwelling. In this paper, the vocalizations of wild Asian elephants from southern India are presented.

The Asian and African elephants are believed to have diverged from a common ancestor in the African continent about $(5-6)\times 10^6$ yrs. ago (Maglio, 1973; Sukumar, 2003). Comparing the vocal repertoires and social contexts of the calls of the two species could give us insight into the pattern of evolution of signal structure and function in an acoustic communication system. Elephants, both African and Asian, live in groups and have a complex social structure (Moss and Poole, 1983; Sukumar, 1989). Elephant herds typically consist of related females and their offspring, including subadult males (Moss, 1988; Vidya and Sukumar, 2005). Adult males of both Asian and African elephants are often solitary and wander widely, joining herds temporarily in the context of reproduction. Males are also known to temporarily associate with other males to form all-male groups (Poole, 1994; Sukumar 1989). A higher level of social organization, with herds organized into clans, has been observed in both Asian and African elephant populations (Moss and Poole, 1983; Sukumar, 1989, 2003; Wittemyer *et al.*, 2005). Given that elephants may move large distances in search of food and water, acoustic signaling serves as an effective way of communication between males and females, among herd members, and between herds (Poole *et al.*, 1988).

Several studies have characterized the vocal repertoire of both captive and wild African elephants both in terms of the structure of calls and social context (Berg, 1983; Poole *et al.*, 1988; Langbauer, 2000; Leong *et al.*, 2003; Wood *et al.*, 2005; Soltis *et al.*, 2005, Stoeger-Horwath *et al.*, 2007; Leighty *et al.*, 2008) and their transmission in space (Garstang *et al.*, 1995; Larom *et al.*, 1997). The functions of some of the calls have also been examined using playback experiments in the field (Langbauer *et al.*, 1991; Poole,

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1999; McComb *et al.*, 2000, 2001, 2003). Acoustic signatures for individual recognition and the capacity of elephants to differentiate between the calls of different individuals have also been studied, largely in the context of low-frequency rumbles (McComb *et al.*, 2000, 2001; Clemins *et al.*, 2005; Soltis *et al.*, 2005). In contrast, very little is known about either the vocal repertoire or the social contexts and functions of vocalizations in Asian elephants, even though the low-frequency rumbles with their infrasonic components were in fact first recorded in captive Asian elephants (Payne *et al.*, 1986). So far only a brief description of the calls of wild Asian elephants is available (McKay, 1973).

This study presents the first recordings of the vocalizations of free-ranging, wild Asian elephants and classifies them into call types based on quantification of the structural characteristics of the calls. The social contexts of these call types, as well as the structural diversity within one of these call types—the rumble—were examined. This study is meant to provide a baseline description of Asian elephant vocalizations for more detailed field studies along the lines of what has been achieved for the African elephant.

II. METHODS

A. Study area

The study was carried out in the Mudumalai Wildlife Sanctuary (321 km^2, 11°33′ to 11°39′N and 76°23′ to 76°43′E) located in the Western Ghats of southern India. The major types of vegetation found here are tropical semi-evergreen, moist deciduous, dry deciduous, and dry thorn forests corresponding to a distinct rainfall gradient of higher rainfall (~1800 mm annually) in the southwest to lower rainfall (~600 mm annually) in the northeast. Mudumalai, with an average elephant density of about 2 individuals/km^2 (Varman and Sukumar, 1995, and unpublished results for 1993–2006) is part of the Nilgiri Biosphere Reserve as well as Project Elephant Range No. 7 that holds the single largest population of the Asian elephant globally (Sukumar, 2003; Venkataraman *et al.*, 2002).

B. Behavioral and acoustic data collection

Fieldwork was conducted mainly in the dry months (February to May) of 2006 and 2007, in and around waterholes, salt licks, open areas such as swamps or grasslands, and within the forests. Surveys were carried out by vehicle and on foot to locate elephant herds during the day. There were a total of 214 encounters with herds during these surveys. The herds were classified into three major categories, namely, mixed herds (both females and males in all age classes), female herds (no adult or sub-adult males) and male herds (adult and sub-adult males only). Solitary individuals, male or female, were also occasionally encountered. The proportion of adult (>15 years) and sub-adult (5–15 years) males in this population is estimated to be 12.5% (Arivazhagan and Sukumar, 2005) and approximately 11% from our encounters. Elephants were individually identified based on distinguishing characteristics such as ear-fold, tail characteristics, and pigmentation. The age class of individuals was also determined using methods described elsewhere (Sukumar, 1989). Adult and sub-adult individuals were grouped together in a single category (Adults) and juveniles and calves were grouped in a single category (Young).

Acoustic data were acquired using a TASCAM DA-P1 Digital Audio Tape (DAT) recorder (frequency response of 1 Hz–20 kHz) and AKG CK 62-ULS omni-directional condenser microphone–C480B preamplifier combination (frequency response of 10 Hz–20 kHz) at a sampling frequency of 48 kHz. The distance to the herd from the observer ranged from 5 m to 75 m. Sources of noise like wind and vehicle were noted for filtering during data analysis. In addition, video recordings were made using a Canon MV1 Digital Video Camcorder in relatively open areas. The date, time, and location of recordings were recorded. Detailed behavioral observations were carried out along with the audio recordings to categorize elephant behavior for association with different call types. Vocalizing individuals were identified on the basis of typical postures and behaviors (www.elephantvoices.org), for example, position of the trunk and body movements (Table IV), exhibited during calling. The presence of other species in the vicinity of elephant herds was also noted.

C. Acoustic data analysis

The recorded signals were re-digitized using a Creative Sound Blaster A/D card (16 bit) at a sampling rate of 48 kHz and the calls were analyzed for their spectral and temporal properties using MATLAB version 6.5 (The Mathworks, Inc., Natick, MA) and PRAAT 5.1.07 (www.praat.org, Paul Boersma and David Weenink).

1. Estimation of call duration

Noise was removed using the spectral subtraction method (Boll, 1979). A custom-written program was used to automatically detect the onsets and cessations of calls. The high frequencies in the signal beyond one-tenth of its bandwidth were suppressed using a low-pass filter (1024-point, finite impulse response). To compute for the temporal envelope, an 85 ms Hamming window normalized to unity sum was used for smoothing. The modulus of the resulting low-pass signal was then convolved with the smoothing window to obtain an approximate envelope, which has large values in the regions corresponding to the signal. The temporal envelope was further subjected to time-domain thresholding with a hard-threshold criterion, which clamps the values of the envelope smaller than 20% of the peak magnitude to zero. The onsets and cessations of calls could be determined from the thresholded envelope.

2. Estimation of minimum and maximum frequencies

A narrow-band spectrogram was computed and the minimum and maximum frequencies of the calls were determined using their power spectral densities. To estimate the essential bandwidth, the power spectral density (PSD) of the noisy signal was first computed using a Hamming window (20 ms). The PSD of the noise was then estimated using the initial 1 s of the recording. The estimated PSD of the noise was subtracted from that of the noisy signal to yield an esti-

TABLE I. List of measured call features.

Acoustic measures	Definition
Mean F_0	Mean frequency of the fundamental measured over the duration of the call (Hz)
Maximum F_0	Maximum frequency of the fundamental (Hz)
Minimum F_0	Minimum frequency of the fundamental (Hz)
Maximum call frequency	Highest frequency of the call (Hz)
Minimum call frequency	Lowest frequency of the call (Hz)
Frequency range of call	Maximum–minimum call frequency
Duration	Length of call in seconds
Harmonicity	Harmonics-to-noise ratio of call
Peaks 1–7 frequency	Frequencies of the first through seventh spectral peaks in the LPC spectrum
Peaks 1–7 amplitude	Amplitudes of the first through seventh spectral peaks in the LPC spectrum
Rumble start frequency	Frequency of the fundamental at the start of the call (Hz)
Rumble end frequency	Frequency of the fundamental at the end of the call (Hz)
Rumble peaks	Number of observed peaks with a minimum frequency modulation of 4 Hz
Rumble percent to maximum	Time in percentage from signal onset to maximum frequency of fundamental
Rumble percent to minimum	Time in percentage from signal onset to minimum frequency of fundamental
Rumble mean modulation	Frequency change per unit time for the fourth harmonic

mate of the PSD of the signal. In general, the estimate had positive values at all discrete Fourier transform (DFT) bins; any negative values (due to estimation errors) were clamped to zero. From this estimate, the bandpass region containing about 80% of the total energy was considered as the frequency range of the signal.

For rumbles, however, calls were first low-pass-filtered with a cutoff of 250 Hz (this value was based on a preliminary inspection of the spectrograms). The signals thus obtained were re-sampled (by the zero padding approach) to obtain more points along the frequency axis (Oppenheim and Schafer, 1989). Spectrograms of these signals (DFT with Hamming window size of 5 ms, 50% overlap) were used for further analysis.

3. Pitch, spectral envelope, and harmonicity analyses

Pitch, spectral envelope, and harmonicity analyses were carried out using PRAAT 5.1.07 (www.praat.org, Paul Boersma and David Weenink). Pitch analysis was carried out using a pitch floor of 10 Hz for rumbles and 100 Hz for most other calls. Spectral envelope analysis was carried out using linear predictive coding (LPC). Calls other than rumbles were re-sampled at 16 000 Hz whereas rumbles were re-sampled at 600 Hz. LPC analysis was carried out using the autocorrelation method with a time step of 0.005 s and a window length of 0.005 s (0.05 s for rumbles). Harmonicity (harmonics-to-noise ratio) was analyzed using the cross-correlation algorithm with a time step of 0.05 s except for chirps, for which 0.005 s was used due to the short duration of the calls.

4. Measured call features

Calls of different age-sex classes (adult male, adult female, young male, and young female) were analyzed separately. The measured features include the call frequency range, duration, harmonicity, as well as mean, minimum, and maximum values of the fundamental frequency (F_0) (Table I). In addition, the frequencies and amplitudes of the LPC peaks were measured to examine spectral patterning. The analyzed acoustic features were separated according to the four age-sex classes and compared statistically (for all categories where the sample size was ≥ 3) for each call type using a combination of one-way analysis of variance and pair-wise comparisons of means by unpaired *t*-tests. The fea-

TABLE II. Sample broken down by age-sex class and behavioral context.

			Number of female individuals		Number of male individuals			Number of calls	
Call type	Total number of calls	Total number of individuals	Adult	Young	Adult	Young	Individuals of unknown sex	Known context	Unknown context
Trumpet	77	37	27(58)	4 (9)	3 (5)	1 (1)	2 (4)	71	6
Roar	56	21	12 (42)	4 (6)	3 (3)	0	2 (5)	51	5
Chirp	68	25	18 (53)	···	4 (10)	···	3 (5)	66	2
Rumble	57	26	14 (27)	1(2)	0	2 (4)	9 (24)	56	1

Values in brackets are number of calls.

TABLE III. Spectral and temporal features of the four major call types.

Acoustic measures	Sex	Age group	Call type: Trumpet	Roar	Chirp	Rumble
Mean F_0 (Hz)	Female	Adult	677.5 ± 29.1	592.8 ± 93.7	Unmeasurable[a]	18.9 ± 1
		Young	787.8 ± 49.3	662.9 ± 165.2	Unknown[b]	20.5
	Male	Adult	828.1 ± 34.8	604.1 ± 53.7	Unmeasurable[a]	Unknown[b]
		Young	607.8	Unknown[b]	Unknown[b]	15.6
Minimum F_0 (Hz)	Female	Adult	607.4 ± 24.5	403.9 ± 51.3	Unmeasurable[a]	11.5 ± 0.7
		Young	697.3 ± 62	516.5 ± 130.4	Unknown[b]	11.8
	Male	Adult	745.6 ± 40.2	386.4 ± 99.1	Unmeasurable[a]	Unknown[b]
		Young	530.0	Unknown[b]	Unknown[b]	10.5
Maximum F_0 (Hz)	Female	Adult	864.60 ± 83.5	1214.5 ± 221.2	Unmeasurable[a]	29.4 ± 3.4
		Young	853.3 ± 56.4	751.2 ± 186.4	Unknown[b]	34.3
	Male	Adult	878.9 ± 47.5	1274.4 ± 471.6	Unmeasurable[a]	Unknown[b]
		Young	645.4	Unknown[b]	Unknown[b]	24.3
Call duration (s)	Female	Adult	0.7 ± 0.1	2 ± 0.3	0.2 ± 0.04	5.4 ± 0.6
		Young	0.7 ± 0.1	1.2 ± 0.3	Unknown[b]	2
	Male	Adult	1.3 ± 0.5	1.5 ± 0.4	0.2 ± 0.03	Unknown[b]
		Young	0.7	Unknown[b]	Unknown[b]	4.5
Harmonicity[c] (lower and upper quartile)	Female	Adult	6.7(5.3,8)	1.9(0.5,3.6)	−0.1(−1.2,4.7)	6.3(5.1,8.1)
		Young	6.3(5.6,7.1)	0.4(0.1,1.6)	Unknown[b]	4.8
	Male	Adult	6.8(6.6,7.6)	1.1(−0.2,2)	5.2(3.5,7.5)	Unknown[b]
		Young	2.1	Unknown[b]	Unknown[b]	5.9

Values are ± standard error. One call was randomly selected for individuals with multiple calls.
[a]Unable to extract fundamental.
[b]Call type not present in sample.
[c]Median values are reported for harmonicity since the distributions were skewed.

tures compared included mean F_0, minimum F_0, maximum F_0, call duration, harmonicity, and frequency and amplitude of the peaks of the LPC spectrum.

For the rumbles, the start and end frequencies of F_0, and percentage time from the start to the maximum and minimum frequencies were measured (Table I). To characterize the frequency modulation in finer detail two measures were used (Table I). The fourth harmonic of all calls was used since visual inspection of the spectrograms revealed that the modulation could be measured at high resolution across almost all recordings whereas the fundamental was sometimes contaminated with noise. The higher harmonics may also have greater functional relevance in social recognition as argued by McComb *et al.* (2003) based on playback experiments on wild African elephants. The first measure was the number of observed peaks in the fourth harmonic of each call, determined visually from the spectrogram with a minimum frequency modulation of 4 Hz as a cutoff. The second measure was the frequency change per unit time for the fourth harmonic, measured by the cumulative change in frequency divided by the time of the call (window length of 200 ms).

To detect the presence of structural subtypes within the rumbles, 13 measured call features (except harmonicity and LPC peaks) were used to generate pair-wise Euclidean distances between calls. The distance matrix was then subjected to cluster analysis using the Unweighted Pair Group Method with Arithmetic mean (UPGMA) (Sneath and Sokal, 1973; Manly, 1986). All statistical analyses were performed using STATISTICA (1999, Statsoft Inc., Tulsa, USA).

III. RESULTS

A total of 371 calls were recorded from 154 individuals. Of these, 258 calls were analyzed from 109 individuals, consisting of 14 males and 95 females (Table II). The remaining calls were discarded on account of low signal-to-noise ratio or overlap with other calls due to simultaneously vocalizing individuals. Based on structural characteristics, the calls could be classified into four types, namely, trumpets, chirps, roars, and rumbles (Fig. 1). One of the call types, the rumble, could be distinguished by its unique frequency range (10–173 Hz, Fig. 1, G–I), which was much lower than that of the other calls. Chirps were distinguished by their unique temporal structure (Table III, Fig. 1, J–K): they were typically of much shorter duration (0.2 s ± 0.1 s) than the other calls. Trumpets and roars differed from chirps in their duration (mean = 1 s and 2 s, Table III). Although both trumpets and roars shared the same frequency range, as revealed by their spectral peaks (Fig. 2), the decrease in power with increasing frequency was steeper in roars. Roars also had significantly lower harmonicity than trumpets (Table III, Mann–Whitney U test, $U=313$, $Z=-7.8$, and $P<0.0001$).

There were no significant differences between the different age-sex classes in all of the call features that were examined in roars, chirps, and rumbles. The only significant differences were between adult male and female trumpets, wherein females had significantly lower mean F_0 and minimum F_0 (unpaired t-tests, $P=0.015$, $t=2.45$ and $P=0.043$, $t=2.78$) than males (Table III).

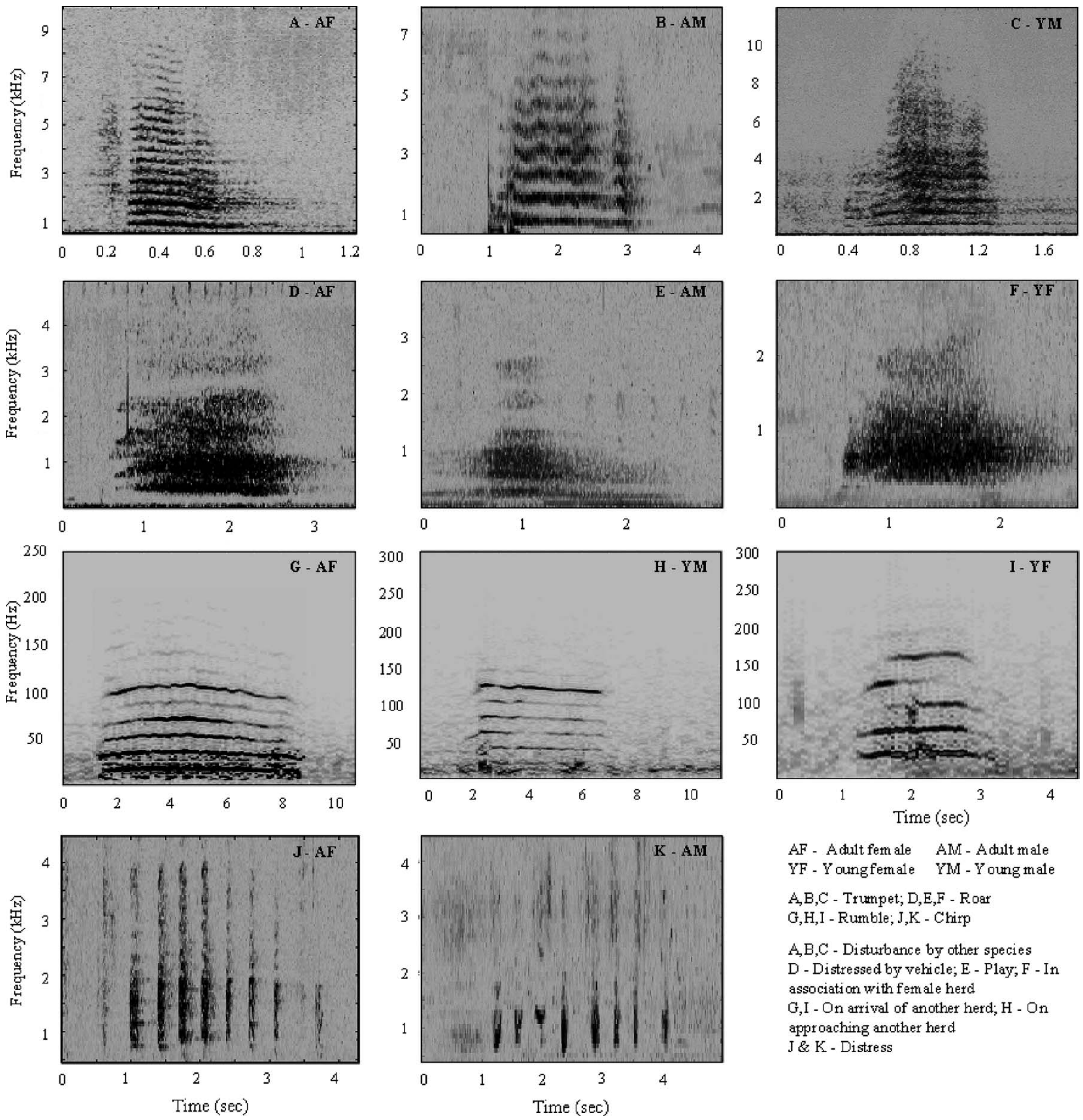

FIG. 1. Spectrograms of examples of the four call types. Sampling frequency for all calls was 48 kHz with 50% overlap. Window size is 100 ms for trumpet, roar, and chirp, and 200 ms for rumbles. Note the different Y-axis scale in G–I.

The different call types were associated with characteristic body postures and behaviors of the vocalizing individual and other members of the herd. These are described in detail in Table IV.

A. Trumpets

Trumpets were loud, conspicuous high-frequency calls. They were in the frequency range of 405–5879 Hz with a mean duration of about 1 s (Table V). They had a rich harmonic structure with at least seven clearly visible harmonics (Fig. 1, A–C). Spectral envelope analysis revealed the first frequency peak to be at 706 Hz (Fig. 2). The fourth frequency peak (at 3078 Hz) was about 13 dB lower in amplitude than the first frequency.

Out of 73 trumpets where the age-sex class was unambiguous, 58 (79.5%) were produced by adult or sub-adult females, nine (12.3%) by juvenile females, five (6.8%) by adult or sub-adult males, and one (1.4%) by a juvenile male (Table II). Out of the 71 trumpets where the context was clear, seven (9.9%) were in the context of play, 17 (23.9%) in the context of disturbance by humans or vehicles, 29 (40.8%) in the context of disturbance by other non-human species, ten (14%) in the context of inter-specific aggression, and eight (11.2%) while running out of a waterhole (Fig. 3). Specifically, trumpeting was observed while encountering other species such as deer (*Axis axis*), gaur (*Bos gaurus*), dhole (*Cuon alpinus*), bears (*Melursus ursinus*), tigers (*Panthera tigris*), egrets (*Egretta garzetta*), and humans.

B. Roars

Roars were noisy, long calls that were in the frequency range of 305–6150 Hz and had a mean duration of about 2 s (Table V, Fig. 1, D–F). They were in the same frequency range as trumpets and their spectral patterning was also simi-

TABLE IV. Social contexts of different call types.

Call type	Context	Vocalizing individual associated posture/behavior	Other herd members associated posture/behavior	Total number of calls
Trumpet	Play	Run after, lash out with trunk	Panic running, vocalize	7
		Head wagging, flop trunk on head	Bouts of agitated movement	
		kick back, test mouth	No visible response	
	Disturbed by humans/vehicle	Advance, J sniff	Bunch, panic running	17
		Foot stomping, redirected aggression	Vocalize, foot stomping, ear flapping	
		Charge, run away, panic running	Bouts of agitated movement	
		Bouts of agitated movement	Trunk twining with other individuals	
			Test mouth/temporal area of others	
	Disturbed by other species	Face other individuals, J sniff	Vocalize, bouts of agitated movement	29
		Run away, charge, panic running	Run away, ear flapping, stand still	
		Run after/raised trunk/trunk lashing	Bunch and advance	
		Bouts of agitated movement, redirected aggression	Huddle calf in between	
		Head shaking, ear flapping, foot stomp, and kick dust		
	Aggression	Charge, run away, lash out with trunk	Run away, retreat from, panic running	10
		Run after, J sniff	Vocalize, no visible response	
	Run out of water hole/exiting	Run out	Run out, no visible response	8
	Unknown context	Facing the landscape, panic running, run away	Vocalize, bouts of agitated movement	6
			Panic running, run away, no visible response	
Chirp	Disturbed by humans/vehicle	Head shaking, tail raised	Vocalize, bunch	30
	Disturbed by other species	Run in circles, redirected aggression	Panic running	26
	Separation from herd	Foot stomping, kick dust	No visible response	4
	Aggression within group	Run in circles, redirected aggression		6
	Unknown context			2
Roar	Play	Wallow, run after, lash out with trunk	Vocalize, wallow, panic running	7
	Disturbed by humans/vehicle	Advance toward, charge, panic running	Vocalize, bunch retreat from	4
	Disturbed by other species	Head shaking, ear flapping, foot stomping	Vocalize, bouts of agitated movement	28
		Charge, run away, redirected aggression	Run away, ear flapping, stand still	
		Panic running, bouts of agitated movement	Bunch and advance, bunch calf in between	
	Aggression	Pushing, dueling, run after, kick dust	Pushing, dueling	3
		Charge, run after	Retreat from, panic running	
	Facing another group/landscape	Stand still, face approaching herd or heterospecific	Vocalize, advance toward	9
		Advance toward, run after	No visible response	
	Unknown context	Panic running	Panic running	5
Rumble	Disturbed by humans/vehicle	Stand still, head shaking, foot stomping	Vocalize, bouts of agitated movement	20
		Bouts of agitated movement, run away	Grouping and exit, ear flapping	
		Scanning, ear spreading, redirected aggression	Group approaches	
		J sniff, ear flapping	Bunch around vocalizing individual	
		Face other individuals and vocalize	Huddle calf in between	
	Disturbed by other species	Stand still, bouts of agitated movement	Vocalize, J sniff, group and exit	6
		J sniff, redirected aggression	Ear flapping, head shaking, stand still	
		Head shaking, foot stomping, ear flapping	Panic running, run after	
	Let’s go	Let’s go stance	Group and exit area	3
	Contact call	Scanning listening, move ahead, vocalize	Vocalize, stand still, listening	3
	Interactive rumbling (intra- and inter-group interactions including greeting)	Stand still, scanning, pushing	Vocalize, group and advance toward	24
		Intermittent touching, trunk twining with conspecifics	Stand still, ear flapping	
		Testing mouth/temporal area of others	Advance toward, retreat from, follow	
		Ears spread, facing another group	Intermittent touching	
		Stand still followed by swing trunk movement	Testing mouth/temporal area of others	
	Unknown context	Running	Follow	1

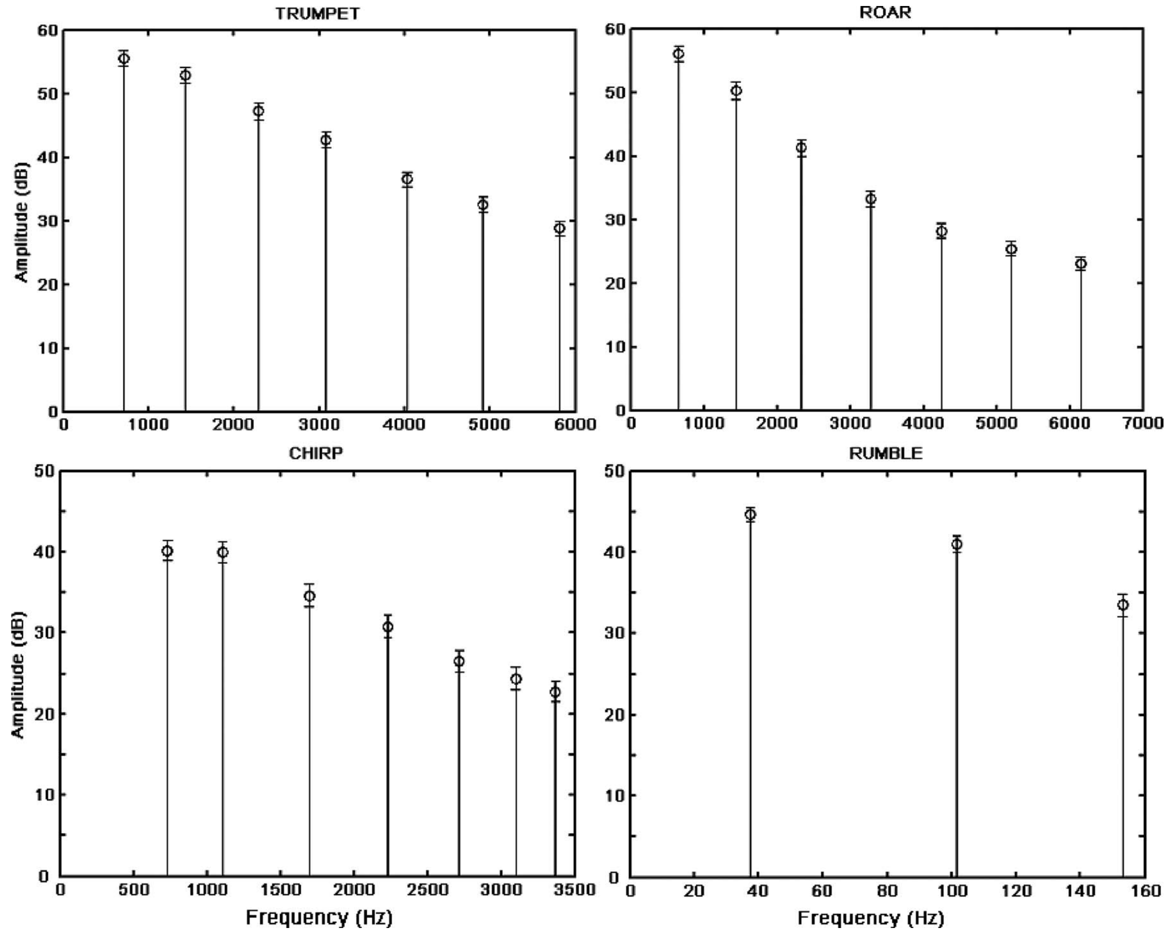

FIG. 2. Spectral envelopes of the four call types obtained using linear predictive coding. Values were pooled across the four age-sex classes since there were no statistically significant differences in the frequencies and amplitudes of peaks of the LPC spectrum in any of the call types.

lar with seven frequency peaks (Fig. 2), the first frequency peak being at 656 Hz. The amplitude fell steeply with increasing frequency, the fourth frequency peak being 23 dB below the first (Fig. 2). This was in contrast to trumpets, where the fourth frequency peak was about 13 dB below the first (Fig. 2). Roars also showed significantly lower harmonicity than trumpets (Table III). Both of the above are probably responsible for the unique perceptual quality of roars compared to trumpets.

Out of 51 calls where the age-sex class was clear, 42 (82.3%) were produced by adult or sub-adult females, six (11.7%) by juvenile females, and three (5.8%) by adult or sub-adult males (Table II). Out of 51 cases where the context was clear, seven (13.7%) were produced during play, four (7.8%) due to disturbance by humans or vehicles, 28 (54.9%) in the context of encounters with other non-human species, three (5.9%) during inter-specific aggressive interactions, and nine (17.6%) while facing another group or on entering a landscape (Fig. 3).

C. Chirps

Chirps were found to lie in the frequency range of 313–3370 Hz (Table V) and were produced in a series (Fig. 1, J–K) ranging from 2 to 8 (mean number $=5.2\pm2.6$, $n=25$ individuals) in a single bout. The duration of a bout of chirping ranged from 0.68 s to 3.8 s. Spectral envelope analysis revealed up to seven discernible frequency peaks (Fig. 2), with the first two peaks having equal amplitude. Although chirps had seven frequency peaks, the range over which these peaks were distributed was much narrower (Fig. 2) than in the case of trumpets and roars. Chirps showed significantly lower harmonicity than trumpets and rumbles (Table III, Mann–Whitney U-test, $U=995.5$, $Z=-4.38$, $P<0.0001$, and $U=786.5$, $Z=-3.8$, $P<0.0001$).

Out of 63 chirp bouts where the age-sex class was clear, 53 (84%) were produced by adult or sub-adult females and ten (15.9%) by adult or sub-adult males (Table II). Out of 66 cases where the context was clear, 30 (45.5%) were due to disturbance by humans or vehicles, 26 (39.3%) due to disturbance by other non-human species, four (6%) in the context of separation of an individual from the herd, and six (9%) during intra-group aggression produced by an individual other than those directly involved in the aggression (Fig. 3).

D. Rumbles

Rumbles were the only call type in the repertoire with infrasonic components. Rumbles were found to lie in the frequency range of 10–173 Hz, with a mean duration of 5.2 s (Table V). They had a distinct harmonic structure (Fig. 1, G–I, Table III), similar to trumpets ($U=1508$, $Z=0.616$, and $P=0.54$). Spectral envelope analysis revealed three peaks,

TABLE V. Comparison of call features of Asian and African elephants

Call type	Call feature	Asian elephant	African elephant
Trumpet	Mean F_0 (Hz)	696.4 ± 20.3	390[a], 300[b]
	Frequency range call (minimum to maximum) (Hz)	405–5879	300–3 000[b]
	Dominant frequency[c]	706.3 ± 21.2	695[a]
	Duration (s)	0.9 ± 0.1	2[a], 1–5[b]
Roar	Mean F_0 (Hz)	649.5 ± 30.8	Unmeasurable[a]
	Frequency range call (minimum to maximum) (Hz)	305–6150	Unknown
	Dominant frequency[c]	656.5 ± 29	574[a]
	Duration (s)	2.0 ± 0.2	3.8[a]
Chirp (bark)	Mean F_0 (Hz)	Unmeasurable	Unmeasurable[a]
	Frequency range call (minimum to maximum) (Hz)	313–3370	Unknown
	Dominant frequency[c]	731.9 ± 26.9	629[a]
	Duration (s)	0.2 ± 0.01	0.47[a]
Rumble	Mean F_0 (Hz)	20.3 ± 0.7 (14–24[d])	27.7[e], 12[b]
	Frequency range call (minimum to maximum) (Hz)	10–173	12–200[b]
	Dominant frequency[c]	37.4 ± 2.9	Unknown
	Duration (s)	5.2 ± 0.3	4.1[e], 1–10[b]
Let's go	Mean F_0 (Hz)	18.5 ± 0.1	15[f]
Contact call	Mean F_0 (Hz)	21.2 ± 1.9	18[f]

Values are ± standard error.
[a]Berg (1983).
[b]Leong *et al.* (2003).
[c]The frequency peak with the highest amplitude in the LPC spectrum.
[d]Payne *et al.* (1986).
[e]Wood *et al.* (2005).
[f]Poole *et al.* (1988).

with the first peak at 37 Hz (Fig. 2). The power of the third peak was about 11 dB lower than that of the first frequency (Fig. 2).

Of the 33 cases where the identity of the rumbling individual was unambiguous, 27 (81.8%) were produced by adult or sub-adult females, two (6.1%) by juvenile females, and four (12.1%) by juvenile males (Table II). Out of 56 cases where the context of rumbling was clear, 20 (35.7%) were produced due to disturbance by humans or vehicles, six (10.7%) due to disturbance by non-human species, three (5.4%) by matriarchs to assemble the group ("let's go" rumble), three (5.4%) in the context of contacting other herd members (contact calls), and 24 (42.9%) during intra- and inter-group interactions at close range (Fig. 3).

Cluster analysis based on the distance matrix of pairwise measures of overall similarity between calls did not reveal discrete structural groups, suggesting that the variation in call structure is graded. Examination of the spectrograms, however, revealed differences between calls, particularly in the direction and extent of frequency modulation. Some calls showed an overall downward modulation of frequency [Fig. 4(A)], others showed little or no frequency modulation [Fig. 4(B)], and some showed an overall upward modulation in frequency [Fig. 4(C)]. Yet another type contained extensive frequency modulation within the call [Fig. 4(D)]. Preliminary comparisons did not reveal any particular correspondence between these features and either age-sex class or behavioral context, but the sample sizes for many of the groups are too small to permit meaningful conclusions at this stage.

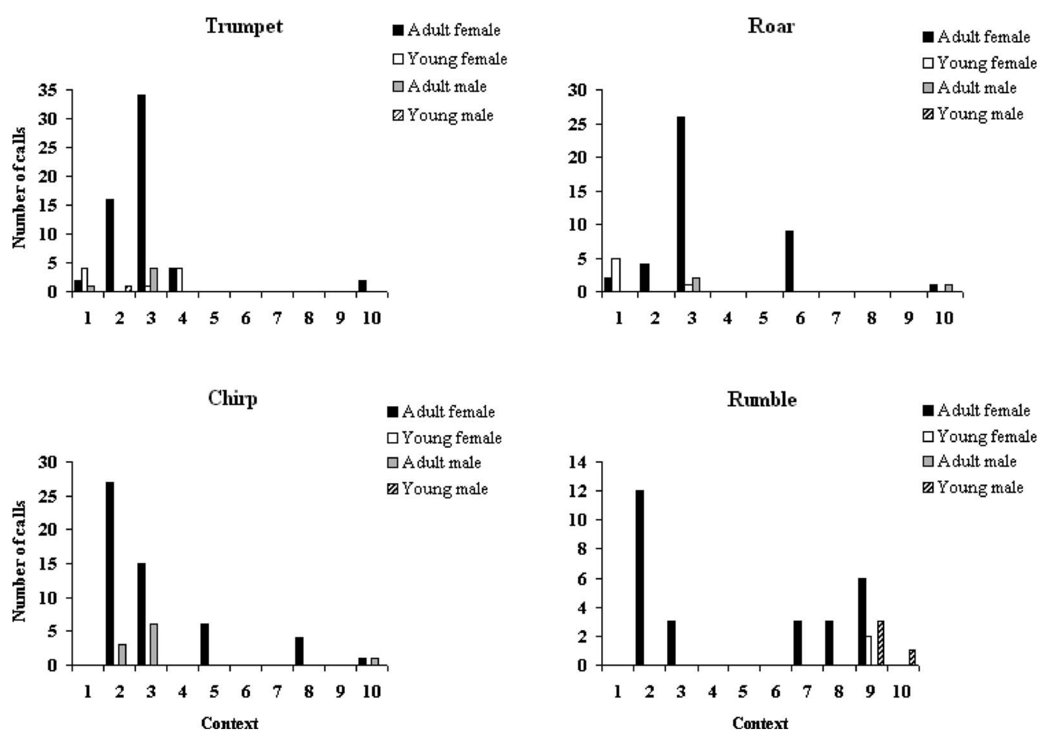

FIG. 3. Call usage according to age-sex class and social context: 1-Play, 2-disturbed by humans/vehicles, 3-disturbed by other species, 4-running out of waterhole, 5-aggression within group, 6-facing another group, 7-let's go, 8-contact call, 9-interactive calling, and 10-unknown.

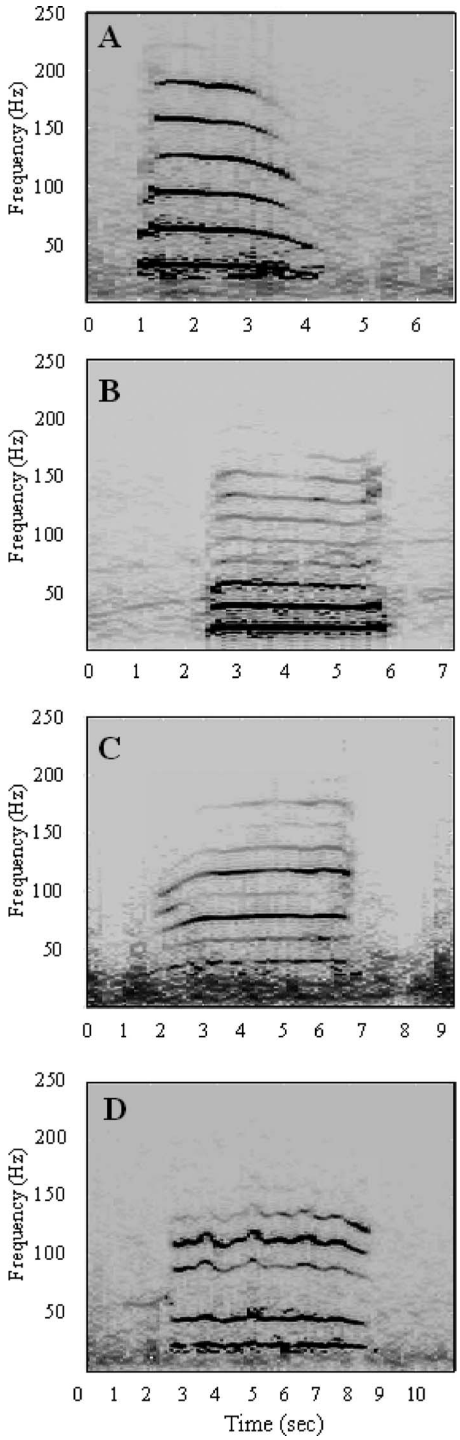

FIG. 4. Spectrograms of calls exemplifying four types of rumbles: (A) downward frequency modulation, (B) little or no frequency modulation, (C) upward frequency modulation, and (D) high modulation frequency within the call. Sampling frequency for all calls was 48 kHz with 50% overlap and window size is 200 ms.

IV. DISCUSSION

A. Structure and classification of calls

This study of the vocalizations of wild Asian elephants classifies them into four mutually exclusive categories based on structural features: trumpets, chirps, roars, and rumbles. Three of the four call types, namely, trumpets, chirps, and roars show extensive overlap in their frequency ranges. They are, however, clearly distinguishable from each other by their temporal and/or spectral structures. Trumpets show high harmonicity relative to chirps and roars, which are noisy. Chirps may be distinguished from roars by their characteristic temporal and spectral structures: short durations and frequency peaks over a narrower range. Roars exhibit low harmonicity and have no specific temporal structure. Rumbles, which constitute the fourth call type, do not overlap with any of the other call types in frequency and exhibit a distinct harmonic structure. Rumbles are also much longer in duration compared with the other call types. Our observations can be compared with previous studies on Asian and African elephants.

On the basis of auditory assessments in the field and visual assessments of a few spectrograms, McKay (1973) classified the vocalizations of wild Asian elephants in Sri Lanka and zoo elephants into three "basic sounds" with eight "resulting sounds," depending on their modification by change in amplitude, temporal patterning, and stressing of overtones, as well as non-vocal sounds produced in the trunk. However, the spectral and temporal characteristics were not defined. These "basic sounds" (with "resulting sounds") were growl (growl, rumble, roar, and "motorcycle"), squeak (chirp and trumpet), and snort ("snort" and "boom"). It is now clear that the categories of resulting sounds such as rumbles and motorcycle with infrasonic components are structurally different from roars, which are calls with low harmonicity and no infrasonic frequencies. Similarly, the chirp and the trumpet are sufficiently different in their spectrograms not to be placed together under the basic sound squeak. Non-vocal sounds such as snort and boom are not considered here since our study was confined to vocalizations. Several observers including Sanderson (1878), Krishnan (1972) and McKay (1973) also described calls of Asian elephants that clearly indicate low frequency sounds. A study on captive female Asian elephants by Payne *et al.* (1986) later recorded infrasound with fundamental frequencies of 14–24 Hz and 10–15 s duration.

There have been a number of attempts at classifying African elephant vocalizations, with most of the studies focusing on infrasound. One of the earliest studies on the African species (Berg, 1983) described the characteristics of the vocalizations of a group of captive elephants based on visual inspection of spectrograms and divided them into ten call types. Our recordings of Asian elephant vocalizations show correspondence with three of these ten types, namely, trumpets, roars, and barks [which we refer to as chirps in accordance with McKay (1973)]. The trumpets and roars recorded by Berg (1983) are longer in duration (2s and 3.8s) but similar in terms of dominant frequencies to our recordings (Table V). On the other hand, Poole *et al.* (1988) classified the low-frequency calls (rumbles) of wild African elephants into seven types based on social context. The fundamental frequencies of the Asian elephant contact calls (21.2 Hz) and let's go rumbles (18.5 Hz) are comparable to those reported by Poole *et al.* (1988) for the African elephant (Table V). More recently, Leong *et al.* (2003) provided a quantitative framework for the classification of the acoustic repertoire of captive African elephants. They described eight categories of calls, namely, trumpet, snort, croak, rev, chuff, noisy rumble, loud rumble, and rumble. Calls similar to the noisy rumbles and loud rumbles described by Leong *et al.* (2003) were not recorded in this study. The rumbles recorded in this study correspond to their third category of rumbles where the maximum frequency is below 250 Hz. The Asian elephant trumpets, on the other hand, lie in a higher frequency range (approximately 400 Hz–6000 Hz) than those reported by Leong *et al.* (2003) for captive African elephants (Table V). Interestingly, they did not report the occurrence of two commonly observed call types, namely, roars and chirps, possibly because their study was carried out on captive elephants. Comparisons of different studies of elephant acoustic communication should take into account possible differences between free-ranging and captive animals, especially those in confined spaces as in zoos. Although only four call types are reported in this study, which was confined to vocalizations, there may exist other types of calls that were not represented in our recordings.

Elephant rumbles clearly show the highest structural diversity and attempts have been made to classify them into subtypes based on quantitative analyses of a number of acoustic features. Using a spectral cross-correlation analysis on the F_0 contour, Leong *et al.* (2003) classified rumbles into five groups, which differ in the extent of frequency modulation and duration. Soltis *et al.* (2005) failed to find distinct rumble subtypes in their study on captive African elephants. On the other hand, Wood *et al.* (2005) classified rumbles of wild African savannah elephants into three types based on the profile of the second harmonic. These differ primarily in the duration and extent of frequency modulation. Our analyses of Asian elephant rumbles, based on their spectral and temporal characteristics, did not show discrete clusters based on measures of overall structural similarity, suggesting that the variation in call structure is graded. Another possibility is that most of the variation occurs in only a few structural features and this is not captured by measures of overall similarity such as the Euclidean distance. The fact that distinct patterns of frequency modulation are clearly visible in spectrograms suggests that this may be the case.

B. Social context

Approximately 80% of the calls across all call types were made by adult or sub-adult females. Juveniles vocalized mostly in the context of play or distress. Both male and female juveniles produced three of the four call types, namely, trumpets, roars, and rumbles. They did not, however, produce chirps. The frequency of adult male vocalizations is low in our sample, but this should be interpreted with caution, since the numbers of adult males that were encountered was low.

Each of the four call types was produced in a variety of contexts and multiple call types were observed in any given context. The three major contexts in which trumpeting was observed are play (largely in the younger age classes), disturbance by humans or other species, and aggression (while charging individuals of other species or vehicles). Chirping was observed in groups that were confused or alarmed by the presence of other species (predators or otherwise) or vehicles. In the former context, the calling individuals were apparently able to detect the presence of other species through smell and they often lifted their trunks in the general direction of the source. This call typically elicited confused running and/or bunching among the other members of the herd. Another context in which this call was observed was when individuals were separated from their herds. Chirps thus seem to be associated with a state of distress or conflict within an individual.

Elephants roared when a herd first arrived at a location such as a waterhole or upon the arrival of a new herd into the area. Further, the calls were also used in the context of play and presence of other species or vehicles. Additionally, individuals, both males and females, were observed to make these calls during aggressive interactions.

Elephants produced rumbles in a variety of contexts that included interactions within and between herds and during encounters with other species. Rumbling was observed in three of the seven contexts described by Poole *et al.* (1988), namely, let's go, contact calling, and greeting. Adult female members rumbled to assemble the herd while leaving a waterhole (let's go rumble) (Poole *et al.*, 1988) or in situations of disorder and confusion such as encounters with other species or vehicles. Rumbling was observed when herd members were separated from each other and these were probably contact calls. Rumbles were also produced when two or more herds came in contact with one another and in these situations, calls were made in quick succession or simultaneously by multiple individuals, sometimes followed by trunk twining, touching, and sniffing between members of the two herds. Occasionally, adult females rumbled at juveniles involved in aggressive play. During encounters with other species (such as bears and dholes), multiple individuals rumbled simultaneously and repeatedly.

The other four call types described by Poole *et al.* (1988) are in the context of mating behavior, including the estrous rumble by females and the musth rumble by males, of which no recordings were made during the course of our study. Adult male elephants were encountered infrequently at Mudumalai due to high levels of ivory poaching in this population during the 1980s and 1990s (Arivazhagan and Sukumar, 2005). Males that were encountered, including those in musth, rarely vocalized.

At Mudumalai, rumbles were commonly produced in situations of distress and aggression. In contrast to the observations at Kruger, South Africa by Wood *et al.* (2005), no rumbles were observed in the contexts of feeding and resting unless the elephants were disturbed by other species. Trumpets, chirps, and roars were often observed to occur in overlapping contexts, including play, aggression, and disturbance. Chirps and rumbles, however, were not observed during play.

V. CONCLUSIONS

A preliminary characterization of the Asian elephant vocal repertoire has been presented, which classifies calls into four call types. Our sample sizes for the different call types are relatively small; this was on account of the often limited visibility within forests and frequent and unpredictable movement of the herds. The sample was also biased heavily toward adult females, with relatively few calls from adult males and juveniles. Comparisons between the calls of different age-sex classes revealed no significant differences in most call features, which was surprising. This will have to be investigated further with larger samples of male and juvenile calls. Although measuring vocalizations of captive elephants can yield large sample sizes in terms of numbers of calls, the social contexts, relative frequencies of call types or even the structures themselves may deviate from those of natural populations due to the confinement, limited living space, and artificial social structure. The data in this study provide a valuable baseline since it was carried out on free-ranging elephants in the wild. Further studies are required to gain more insight into the full extent of the acoustic repertoire and the relations between call structures and social contexts in Asian elephants.

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