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The burst-pulse nature of ‘squeal’ sounds emitted by sperm whales (*Physeter macrocephalus*)

Caroline R. Weir*, Alexandros Frantzis†∫, Paraskevi Alexiadou† and John C. Goold‡

*Ketos Ecology, 4 Compton Road, West Charleton, Kingsbridge, Devon, TQ7 2BP, UK. †Pelagos Cetacean Research Institute, Terpsichoris 21, 16671 Vouliagmeni, Greece. ‡School of Biological Sciences, University of Wales Bangor, Memorial Building, Deiniol Road, Bangor, LL57 2UW, Wales, UK. ∫Corresponding author, e-mail: afrantzis@otenet.gr

Sperm whales (*Physeter macrocephalus*) typically produce sharp onset, broadband pulse sounds at varying repetition rates. Acoustic recordings of different social units of sperm whales in the Mediterranean Sea included apparent non-click sounds of tonal quality, termed ‘squeals’. Quantitative analysis of the spectral signal and waveform indicate that although squeals are perceived as tonal and appear spectrally as narrowband frequency-modulated structures with harmonics, they actually consist of pulses at high repetition rates exceeding 1600 clicks/s. Squeals contained energy at between 400 Hz and 22 kHz, with mean peak energy at the relatively low frequency of 700 Hz. Five spectral forms of squeal could be recognized, with the dominant form (45%) of squeals showing a decrease in frequency along the squeal contour. Mean click repetition rate ranged between 713 and 1385 clicks/s for individual squeals, and also varied within squeals at rates of between 64 and 444 clicks/s. Variation in click repetition rate was reflected in the frequency spacing of the spectral sidebands, in a statistically significant inverse relationship. Squeals were recorded only during bouts of sperm whale social behaviour, consistent with their having a communicative social function. Sperm whale squeals are structurally and audibly similar to the burst-pulse sounds produced by many smaller odontocete species, and might fall on the continuum between distinct click trains and pure-tone whistles.

INTRODUCTION

The sounds emitted by sperm whales, *Physeter macrocephalus* (Linnaeus, 1758), have been intensively studied since they were first identified in the 1950s (Worthington & Schevill, 1957). Sperm whales are highly vocal and primarily produce sharp onset, broadband pulses known as ‘clicks’ at regular repetition rates of 1–2 s (Weilgart & Whitehead, 1988) and with energy reaching 30 kHz (Backus & Schevill, 1966). However, clicks may be emitted at various repetition rates and patterns to produce other defined sounds such as slow clicks/clangs, creaks, chirrups and codas (Gordon, 1987; Weilgart & Whitehead, 1988; Goold, 1999).

While the majority of described sounds emitted by sperm whales consist of clicks, there is some evidence for production of non-click sounds. Sperm whales do not appear to produce the tonal whistles typical of many other social odontocetes. Although Perkins et al. (1966) and Busnel & Dziedzic (1967) report pure tone whistles from sperm whales, these might be attributable to another unseen odontocete species (Gordon, 1987). However, sperm whales may produce a variety of other low intensity sounds. A narrowband ‘trumpet’ with harmonics (Gordon, 1987) has recently been described as a tonal signal (Teloni et al., 2005). Vocalizations variously described as ‘yelps’, ‘squarks’ and ‘chirps’ have been reported from Brazilian sperm whales (Perkins et al., 1966), which Gordon (1987) considers to be a likely result of rapid sequences of clicks. Similar may be true of the ‘short trumpets’ and ‘series of pips’ described by Goold (1999) from entrapped sperm whales in Scotland. Low intensity tonal components have been occasionally heard in the vocalizations from sperm whale calves (Watkins et al., 1988).

Backus & Schevill (1966) note that ‘although all other odontocetes whose sounds have been recorded to date are capable of at least two sorts of vocalization—clicks and squeals – we have heard only the former from sperm whales’. However, recent vocalizations described as ‘squeals’ have been reported from a group of immature male sperm whales off Scotland (Goold, 1999) and from nursery groups of sperm whales in both the Tyrrhenian and Ionian Seas (Drouot, 2003). Squeals were described as narrowband sounds with a frequency-modulated structure perceived as ‘tonal’ to the human ear (Goold, 1999; Drouot, 2003). However, the possibility exists that sperm whales may produce modulated click trains (Backus & Schevill, 1966), and it is currently unclear whether squeals represent a non-click tonal sound or are in fact burst-pulse sounds comprising clicks at very high repetition rates.

Here, we present the first descriptive analysis of squeal sounds from sperm whales and discuss their structure and context.

MATERIALS AND METHODS

Field data collection

Sperm whale squeal sounds were recorded during five years (1999–2003) as part of the long-term ‘Greek Sperm Whale Programme’ of the Pelagos Cetacean Research Institute (Frantzis et al., 2003), along the Hellenic Trench

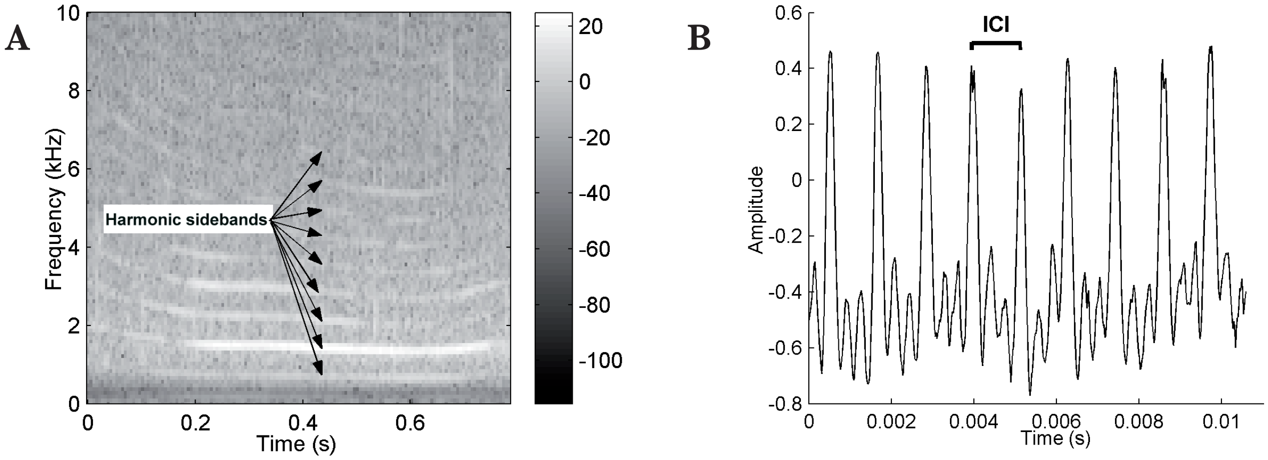

Figure 1. Measurements utilized during squeal analysis: (A) harmonic sideband spacing in a squeal spectrogram; and (B) click amplitude spikes within a squeal waveform, with the inter-click interval (ICI) measured between the top of each spike.

(Greece, eastern Mediterranean Sea). A 16 m vessel was used to approach sperm whales for photo-identification, and visual data collected included the number, sex and age-class of whales, the identification and behaviour of particular individuals within social units (*sensu* Whitehead, 2003; these social units have been studied for nine years) or whale pairs encountered, and the presence of other cetacean species. In the case of the pair of whales, their total length was estimated from coda click inter-pulse intervals (see Gordon, 1991), and their sex was determined through genetic analysis of sloughed skin (ZFX/ZFY technique described by Berubé & Palsbøll (1996); conducted in the Department of Biological Sciences, University of Durham, by Dan Engelhaupt). Acoustic recordings were made continuously during whale encounters, using a hydrophone array towed 100 m behind the vessel. The array comprised two omnidirectional Benthos AQ-4 elements with 30-dB gain preamplifiers, positioned at 3 m spacing along the axis of a 10-m oil-filled polyurethane tube. The frequency response of the elements was flat within the 1 Hz–15 kHz and 15–25 kHz bandwidths (±1.5 dB and 2.0 dB respectively). For all recordings made from 2000 onwards, high-pass filters (520 Hz) were utilized in the field to reduce low frequency noise. The filters used were second order high pass units, with 12 dB/octave roll-off below the break point. The signal was recorded with a Sony TCD-D8 digital audio tape (DAT) recorder (with a built in anti-aliasing filter at 22 kHz), at 48 kHz sampling frequency. The DAT recorder had a flat response from 20 Hz to 22 kHz (±1.0 dB).

Data analysis

A total of 369 squeals was recorded in the field, of which 250 squeals within 96 sperm whale recordings of good signal to noise (S/N) ratio were identified, and short sections (3 s either side of the signal) containing squeals were extracted using CoolEdit 2000 (Syntrillium). To avoid error when assigning particular vocalizations to sperm whales, recordings where other cetacean species (predominantly striped dolphins, *Stenella coeruleoalba*) were present, acoustically or visually, were excluded from the analysis. Only 86 squeals with a high S/N ratio were selected for analysis, after elimination of low amplitude squeals and those that were masked by vessel/water noise and/or other sperm whale sounds. Sound files of individual squeals were created from a single channel (whichever was clearest), and imported into Matlab (Mathworks 13.0) for signal processing analysis. Digital high-pass filters (500 Hz) were applied to squeal files (N=15) originating from the unfiltered field recordings made in 1999 to reduce vessel and water noise. However, recordings with low background noise levels were analysed both with and without digital filters to avoid potentially eliminating low frequency portions of the sperm whale squeal.

We firstly describe spectral characteristics of the 86 individual squeal sounds via spectrograms (time vs frequency) produced within Matlab using a 512-point fast Fourier transform (FFT) (duration 10–11 ms) and modulated with a Hanning window. The descriptive parameters of the squeals were analysed according to standard criteria (frequency range, duration and peak energy) utilized for describing dolphin whistles (Janik et al., 1994) and burst-pulse vocalizations (Dahlheim & Awbrey, 1982). These criteria were used for the sake of convenience, though it was recognized that squeals might represent a different type of sound. Descriptive parameters were measured directly from the Matlab spectrogram using crosshairs to manually log the time and frequency components of the harmonic sideband (see Figure 1A).

Ten squeals of particularly high S/N ratio were subsequently selected for fine-scale waveform analysis, using custom-made scripts in Matlab. Within each squeal waveform the peaks of individual pulses were marked and used to calculate the inter-click intervals (ICIs), defined here as the time difference between the peak signal amplitude of two successive clicks (see Figure 1B). Individual clicks were marked for the duration of the squeal or for as long as they remained clearly identifiable within it. A mean ICI value was calculated for each 10 ms section progressing through the squeal. Clicks were often indistinct at the start and end of each squeal, and were eliminated completely from the waveform when the signal was subject to masking. Only

Table 1. *Average values and ranges (in parentheses) for parameters of all spectral squeal types.*

			Entire visible squeal				Dominant harmonic sideband			
Squeal type	N	Duration (s)	Minimum visible frequency (Hz)	Maximum visible frequency (Hz)	No. of visible harmonic sidebands	Dominant frequency of entire squeal (Hz)	Start frequency (Hz)	End frequency (Hz)	Minimum frequency (Hz)	Maximum frequency (Hz)
Downsweep	39	0.68 (0.31–1.48)	745 (468–1492)	8812 (3718–19258)	7 (2–20)	1193 (601–2249)	1582 (824-2649)	1017 (468–1981)	997 (468–1981)	1674 (779–4297)
Upsweep	7	0.91 (0.50–2.12)	716 (468–1135)	6485 (2560–15473)	6 (3–9)	1606 (646–3584)	1492 (512–3184)	1873 (690–3941)	1473 (468–3273)	1892 (690–3941)
Flat	9	1.22 (0.48–2.78)	903 (468–1358)	7671 (4163–21751)	6 (1–18)	1314 (512–2249)	1304 (512–2293)	1284 (468–2293)	1249 (468–2249)	1353 (557–2338)
Concave	18	1.67 (0.75–3.58)	638 (423–913)	10521 (4475–18545)	9 (4–25)	1274 (601–2338)	1061 (512–2293)	1098 (423–3273)	930 (423–2338)	2038 (601–4163)
Convex	7	0.53 (0.27–0.91)	843 (512–1046)	10493 (3540–21529)	10 (4–18)	1295 (646–2694)	1517 (646–3763)	1581 (735–3629)	1237 (512–2694)	1651 (735–3763)
Variable	6	1.39 (0.70–2.12)	668 (423–1091)	9492 (4968–19169)	10 (5–18)	1195 (690–2248)	1284 (468–3184)	1277 (735–2159)	1039 (423–2071)	1507 (868–3184)
Total squeals	86	1.00 (0.27–3.58)	739 (423–1492)	9045 (2560–21751)	8 (1–25)	1264 (512–3584)	1410 (468–3763)	1196 (423–3941)	1071 (423–3273)	1721 (557–4297)

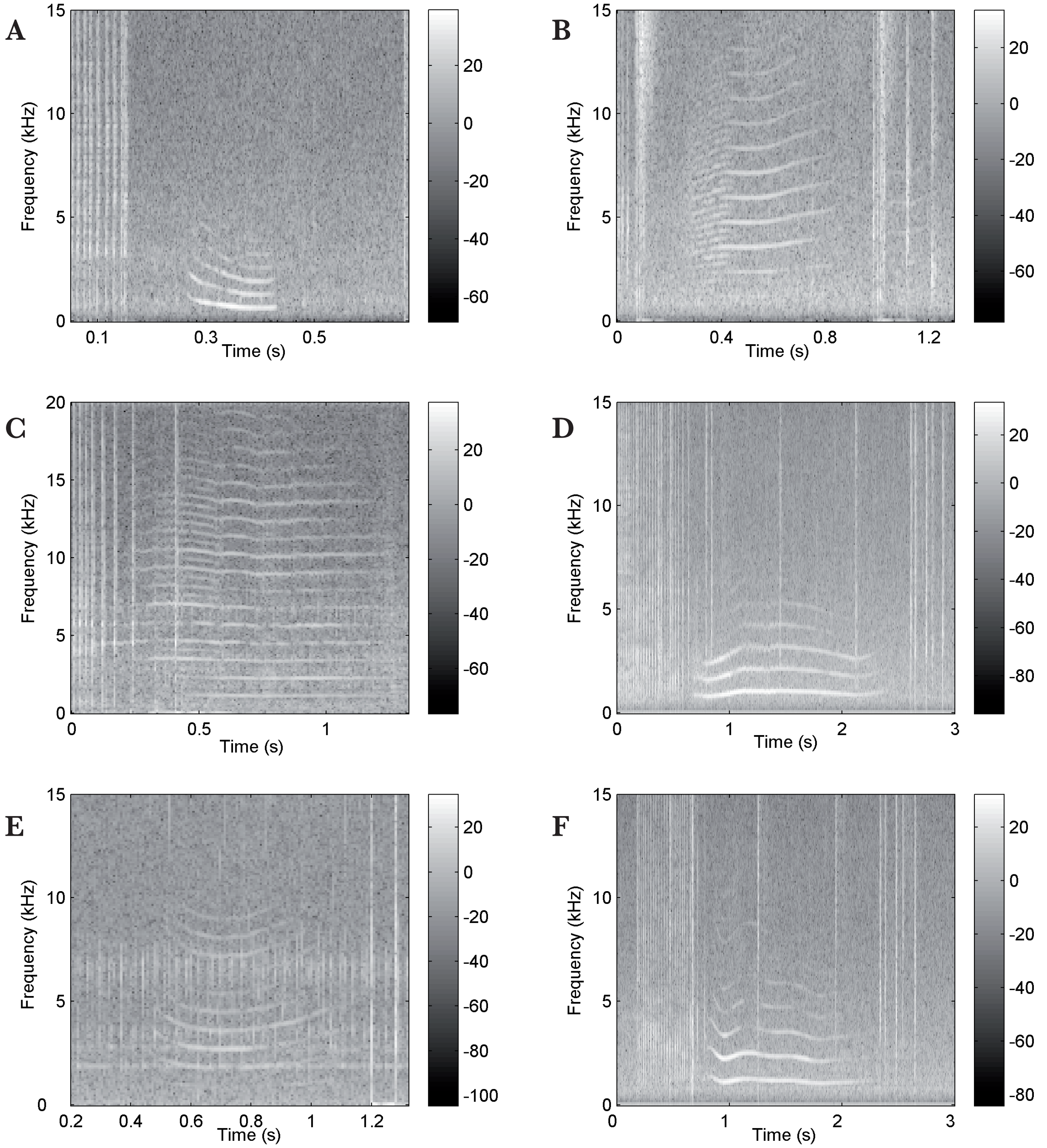

Figure 2. Spectrograms of five different squeal contours: (A) downsweep; (B) upsweep; (C) flat; (D) concave; (E) convex; and (F) variable. Scale bars represent the relative spectral density in dB.

complete 10 ms click segments were therefore used during waveform analysis to ensure that segments were large enough to be truly representative of click rate. The 10 ms segments were also used to analyse changes in click repetition rate along each individual squeal. The frequency spacing (Hz) of sideband components was marked at 50 ms intervals using crosshairs within the spectrogram, under the control of a user written Matlab script. Where the harmonics were indistinct, the nearest value either side of 50 ms was utilized. For descriptive statistical analysis, the Statistical Package for the Social Sciences (SPSS) was used.

RESULTS

Squeal spectral analysis

Spectral representations of squeals showing their sideband structure (i.e. an apparent narrowband frequency-modulated structure with harmonics) are presented in Figure 2. The squeals contained energy at relatively low frequencies, with a mean fundamental frequency of 739 Hz (range=423–1492 Hz, N=86, SD=223). The total frequency range of sperm whale squeals might extend to lower frequencies than reported here, since 71 of the squeals (83%) had been filtered

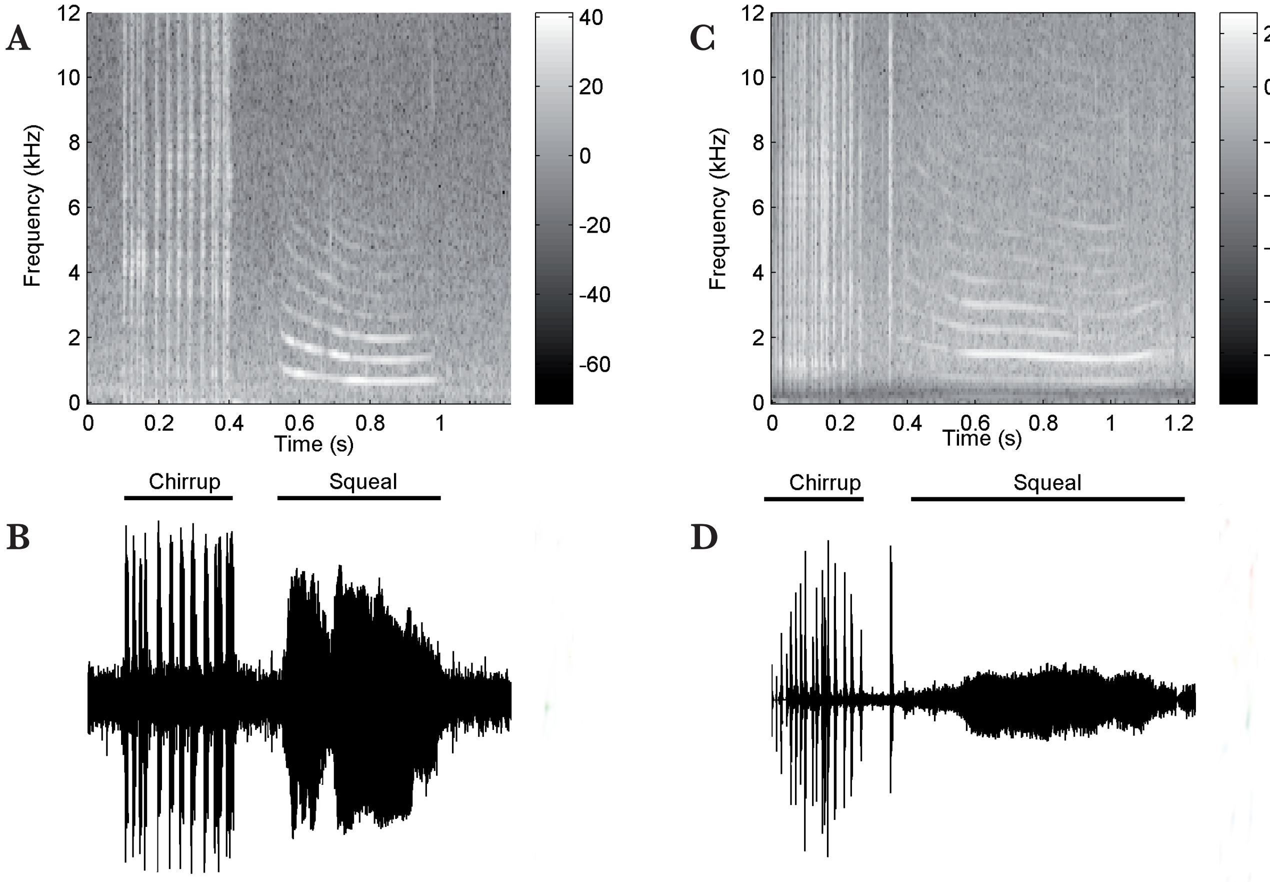

Figure 3. Spectrograms (A&C) and corresponding waveforms (B&D) for two sperm whale squeals. The spectrogram scale bar represents the relative spectral density in dB.

in the field at 520 Hz. It was possible to observe energy at frequencies just below the filter breakpoint in some instances, due to the relatively shallow filter slope. The mean peak frequency of the dominant sideband was also relatively low at 1264 Hz (range=512–3584 Hz, N=86, SD=616). Although the peak energy of squeals occurred below 4 kHz, higher frequency energy was visible within the spectrograms in the form of 1 to 25 sidebands, and the mean maximum frequency measured for the uppermost visible sideband was 9045 Hz (range=2560–21,751 Hz, N=86, SD=4963). Squeals had durations ranging from 0.27 to 3.58 s (x=1.00, N=86, SD=0.63) and longer duration squeals usually exhibited several changes in tone, detectable audibly to the human ear.

The audible change in inflection along a squeal was visible as frequency modulation within the spectral sidebands, and squeals could be assigned to descriptive forms based on the directional gradient of the sideband contours (Figure 2A–E). The descriptive parameters of each squeal type are presented in Table 1. The majority of squeals were described as downsweeps (Figure 2A) where the dominant sideband showed a decrease in frequency (mean variation

Table 2. *Mean ICI and click repetition rate in ten sperm whale squeals of high S/N ratio.*

Squeal No.	Total squeal duration (ms)	No. of 10 ms segments measured	Average mean ICI/10 ms segment (ms) and ranges (in parentheses)	Mean squeal click rate (clicks/s)
1	800	54	1.40 (1.31–1.51)	712.5
2	443	41	0.72 (0.62–0.85)	1384.6
3	469	38	1.37 (1.03–1.54)	729.1
4	338	29	1.34 (1.01–1.57)	745.7
5	1702	129	1.01 (0.92–1.26)	988.1
6	1433	98	0.86 (0.79–0.96)	1162.4
7	393	18	1.16 (1.11–1.19)	860.8
8	854	51	1.28 (1.15–1.46)	781.4
9	1196	55	1.24 (1.15–1.41)	808.8
10	1046	46	1.34 (1.16–1.72)	745.3

Table 3. *Summary of sperm whale encounters where 369 individual squeals were recorded. Abbreviations for group composition consist of presumed adult females bearing calluses (AF), known sub-adult males (SM), young males (YM), calves (C) and juveniles (J). All other animals were of unknown age-class/sex (?), but certainly not mature males.*

Encounter no.	Date	No. squeals isolated	Social unit or pair	Total no. whales	Known group composition
1	25/06/99	52	Chromo	8-9	3–4AF+2J+1C
2	18/07/99	4	Chromo	≥3	≥2AF+≥1J
3	09/08/99	26	Chromo	≥3	≥2AF+≥1J
4	31/08/99	29	Chromo	9	≥1–2AF+≥1J
5	20/07/00	11	Patroklos & Achilleas	2	2 SM
6	23/07/00	2	Patroklos & Achilleas	2	2 SM
7	08/08/00	3	Giagia	≥8	≥2AF+≥1C
8	01/09/00	41	Ippolyti	12	3AF+2C
9	07/09/00	7	Ippolyti	11	2AF+2C
10	09/08/02	3	Zak	6	≥1AF+1J+1C
11	24/08/02	31	Pylos	7	1AF+2C
12	25/08/02	3	Pyl	6	1AF+1J?
13	27/08/02	125	Zak	12	1AF+1YM+1C+1C or J
14	29/07/03	29	Bestend	10	3AF+1YM+1C or J
15	30/07/03	3	Bestend	11	4AF+1AF?+1YM+2J+2C

between start and end frequencies=-565 Hz, N=39, SD=314) over time. Upsweeps had an overall increase in frequency (x=382 Hz, N=7, SD=319) with time (Figure 2B) and were comparatively scarce. Flat squeals (Figure 2C) maintained similar frequency (x=40 Hz; N=9, SD=15) over time. In concave squeals (Figure 2D), the start and end frequency of the squeal were similar (x=280 Hz, N=18, SD=330), but the frequency increased to a mean of 1108 Hz at some point along the contour. Conversely, the convex squeals (Figure 2E) had similar start and end frequencies (x=165 Hz, N=7, SD=126), but showed a mean decrease in frequency of 414 Hz at a point along the contour. Six squeals showed more than one frequency inflection along the contour, and were categorized as 'variable' (Figure 2F).

Squeal waveform analysis

Waveform analysis revealed closely-spaced click sequences that correspond exactly in time with the spectral tonal signal (Figure 3). When examined at fine-scale (resolution of 10 ms), distinct individual spikes were visible within the waveform (Figure 1B).

The mean ICIs of ten squeals with high S/N ratio are provided in Table 2. Calculations of overall mean click repetition rate ranged between 713 and 1385 clicks/s for individual squeals. The maximum click repetition rate recorded in a 10 ms analysis segment was 1622 clicks/s. Variation in the click repetition rate within individual squeals was reflected by changes in the frequency spacing of the sidebands (Figure 4). The sidebands occur as a consequence of spectral rippling within each spectral slice that makes up the spectrogram. The rippling is caused by two or more clicks occurring within each FFT analysis window, and the ripple frequency (i.e. the frequency spacing between ripple peaks) is the simple inverse of the ICI (i.e. 1/ICI). Spectral rippling is a known phenomenon in signal analysis and has been used in sperm whale acoustic research in a different context to estimate body lengths (Goold, 1996). Between 5 and 27 measurements of harmonic sideband were recorded from each of the ten high quality squeals. There was a strong negative correlation between sideband interval and ICI (Spearman's rank order correlation: rs=–0.997, N=117, *P*=<0.001), and variation in click repetition rate therefore accounts for the apparent frequency modulation in the spectral harmonics.

Squeal context

Squeals were recorded during 15 separate encounters with one pair and seven different social units of sperm whales on different dates (Table 3). Social units typically comprised 4–12 individuals (Frantzis et al., 2003) that were mature whales bearing calluses (considered to be females), calves and/or juveniles and immature animals of both sexes. The pair of whales comprised two sub-adult males (9.6 and 9.8 m long respectively) encountered on two separate days.

Table 4. *Relative timing of squeals and chirrups in 40 overlapping pairs.*

Squeal category	N	Preceded start of chirrup	Followed start of chirrup	Within the chirrup	Encompassed the entire chirrup
Downsweep	21	0	20	1	0
Upsweep	3	0	2	0	1
Flat	4	0	3	1	0
Concave	8	0	2	0	6
Convex	1	0	1	0	0
Variable	3	1	1	0	1
Total squeals	40	1	29	2	8

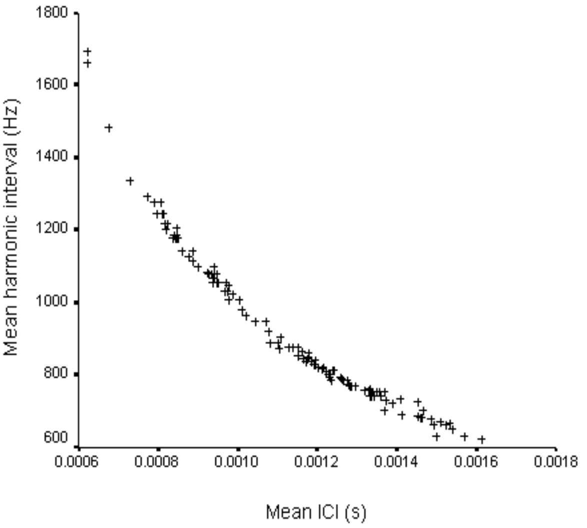

Figure 4. Plot of mean ICI against mean harmonic sideband interval (Hz) measured (where the S/N ratio was adequate) at 50 ms intervals (N=117) along ten sperm whale squeals.

Solitary mature males were frequently encountered during the survey (Frantzis et al., 2003), but squeals were never recorded in their vicinity. The data presented in Table 3 suggest that squeals are not uniquely associated with any particular sperm whale individual or social unit, and are not obviously confined to a particular age-class or sex of whale.

Squeals were produced while sperm whales were actively socializing at, or just below, the surface. The close proximity of other animals prevented identification of vocalizing individuals, and restricted the assignment of squeals to particular behaviours. On one occasion, squeals were produced immediately after two sub-adult male whales fluked up, and prior to the commencement of usual clicks. Otherwise, squeals were never heard while whales were submerged on feeding dives.

Squeals were always recorded during periods when whales were producing other sounds. Of 79 squeals recorded with other whale sounds of high S/N ratio, overlaps occurred more often with rapid or usual clicks (N=44) and chirrups (N=40) than with codas (N=14). The relative timing of squeals and chirrups within overlapping pairs is shown in Table 4. The majority of squeals (N=29) commenced during a chirrup and continued after the chirrup had finished, with a mean timing overlap of 29.3% (range=2–87%) of the squeal duration. The timing of overlaps also varied according to the descriptive category of the squeal (Table 4), with all except one of the downsweep squeals occurring at the end of a chirrup, and the majority of concave squeals beginning and ending either side of a chirrup. Where squeals did not overlap with chirrups, the duration between the last recorded chirrup and the commencement of a squeal ranged from 0 to 10.6 s (N=31).

DISCUSSION

The results presented here indicate that although humans audibly perceive squeals as continuous tonal signals, they actually consist of a series of very rapid individual pulses at measured repetition rates of up to 1622 clicks/s. We believe that these sounds are synonymous with the rapid repetition rate 'burst-pulse' click trains described for many other odontocete species (Herman & Tavolga, 1980), notably killer whales *Orcinus orca* (Dahlheim & Awbrey, 1982), but not previously analysed in sperm whales. Although sperm whale 'creaks' may contain repetition rates as high as 220 clicks/s (Gordon, 1987), more typical values are 50 clicks/s (Madsen et al., 2002) and these signals remain audibly distinguishable to the human ear as clicks rather than developing tonal qualities. The strong relationship between squeal click repetition rate and sideband frequency interval also supports a burst-pulse structure, since a comb spectrum effect (Watkins, 1967) is produced when click repetition rates are greater than the analysed bandwidth, with harmonic sidebands occurring at intervals equivalent to the repetition rate.

Murray et al. (1998) suggest that odontocete vocalizations might form a continuum between sound categories, characterized by an exponential damping of the sinusoidal pulses at one end (click trains) and a continuous sinusoidal signal (tonal whistle) at the other. The signal is graded as a function of time between pulses, and along this continuum burst-pulse sounds form an intermediate sound type. The pulse frequency of odontocete signals can change instantly to produce sounds that are perceived by the human ear to change rapidly between categories (Murray et al., 1998). The squeals produced by sperm whales might therefore be graded signals that are intermediate between click trains and tonal whistles, and are produced when the time interval between the more 'usual' discrete pulses suddenly decreases in frequency.

Descriptive analysis of the squeal spectrogram revealed some consistency between the parameters of individual squeals and broadly agreed with the findings of Drouot (2003). Both studies report short squeal duration (x=1 s) and peak energy at around 1 kHz. This peak energy is much lower than that of sperm whale 'usual clicks' at between 5 and 24 kHz (Madsen et al., 2002). Dahlheim & Awbrey (1982) determined that click repetition rate varied according to call type in killer whales, and our data suggest that at least five forms of squeal may be produced by sperm whales based on frequency inflection related to changes in pulse rate. Downsweep and concave spectral contours were the most frequently observed forms of squeal recorded here and in studies by Goold (1999) and Drouot (2003). The downswept contour showed a steady decrease in click repetition rate over time, and concave contours showed an increase in click repetition rate shortly followed by a decrease. Consequently, these variations are also audibly apparent as changes in pitch.

Whether subtle variations in frequency and pitch of squeal sounds are of significance to sperm whales is unknown. Burst-pulse sounds are often proposed to have a communicative social function in other odontocetes (Herman & Tavolga, 1980), and have been linked to specific social behavioural contexts in some species such as bottlenose dolphins *Tursiops truncatus* (Janik, 2000) and false killer whales *Pseudorca crassidens* (Murray et al., 1998). Although the exact role and context of sperm whale squeals is unknown, their production only by socializing whales is consistent with a communicative function. Chirrups and codas were also present during many squeal recordings, both of which are considered social sounds produced by interacting whales at the surface (Gordon, 1987; Drouot, 2003). Chirrups and codas regularly overlapped temporally with squeals. However, isolated squeals were also recorded and it was not possible to conclude whether overlapping chirrups and squeals were produced simultaneously by one whale (and possibly as an artefact of one another) or whether two different animals emitted the sounds.

We were unable to confirm whether squeals were produced by a particular age-class or sex of sperm whale. Watkins et al. (1988) reported 'slightly noisy, tonal components' in the sounds emitted by sperm whale calves, which they suggested were incompletely formed clicks. However, our data and those of Goold (1999) indicate that the production of tonal-sounding burst-pulse sounds are not limited to calves but are also produced by sub-adult males, and possibly also whales of other age/sex. Although solitary adult male whales were encountered during our study, no squeals were recorded in their presence. Burst-pulse sounds have not been reported in published studies on adult males (Weilgart & Whitehead, 1988; Madsen et al., 2002) or nursery groups elsewhere (Gordon, 1987). However, tonal sounding 'mews' have been heard fairly often from nursery groups in the Pacific (Hal Whitehead, personal communication) and low level tonal sounds have been heard from socializing groups in the Indian Ocean (Jonathan Gordon, personal communication), suggesting that squeals and other tonal-sounding vocalizations may be emitted more frequently by sperm whales than previously thought.

CONCLUSION

Our study indicates that squeals are a product of high repetition click rates of up to 1622 clicks/s, notably higher than the 220 clicks/s previously reported for this species (Gordon, 1987). These sounds are best described as 'burst-pulse' sounds as reported in other odontocete species, with variation in click repetition rate apparent as audible changes in pitch. The context of squeals is unknown, but their production during social interaction combined with an absence during acoustic studies of solitary male sperm whales suggests a communicative role.

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