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BIOACOUSTICS OF SINGING CICADAS OF THE WESTERN PALAEARCTIC: *CICADETTA TIBIALIS* (PANZER)(CICADOIDEA: TIBICINIDAE)

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Abstract - Populations of *Cicadetta tibialis* (Panzer, 1798)(= *Cicadivetta tibialis:* according to BOULARD, 1982) from Slovenia and the North and South Caucasus were studied and compared with data from the literature. The sound repertoire of the species seems to contain only one type of song - the calling song of the solitary male - consisting of two phrases with a species-specific time pattern. Phrase I is a sequence of short echemes followed by a long one; phrase II consists of regularly repeated short echemes (Fig. 3a, b). We present temporal parameters qualitatively and quantitatively. The spectrum of the calling song contains two frequency bands: a main one between 12 and 22 kHz with a maximum between 14 and 18 kHz, and sometimes with a secondary peak near 12 kHz, and a second band with a maximum between 7 and 8 kHz. The latter is better expressed in recordings from close by. Comparisons of data obtained and values from the literature show that populations from Slovenia, Dalmatia (Croatia), and the south Caucasus form a common group, definitely belong in one taxon, whereas the population of the northern Caucasus seems to show some peculiarities both in the anatomy of the genitalia and the temporal characteristics of the calling song. Calling males induce strong substrate vibrations. Vibrational components which we measured at distances of up to 1.3 m, have in a range of a few decimeters two nearly equal spectral peaks in the same frequency range as the air-borne sound, and sometimes secondary peaks near 12 kHz. The farther from the singing male, the more the lower frequency peak dominates.

Izvleček - BIOAKUSTIKA POJOČIH ŠKRŽATOV ZAHODNEGA PALEARKTIKA: *CICADETTA TIBIALIS* (PANZER) (CICADOIDEA: TIBICINIDAE)

Raziskovali smo populacije škržatov *Cicadetta tibialis* (Panzer, 1798)(= *Cicadivetta tibialis* po stališču BOULARDA, 1982) iz Slovenije, južnega in severnega Kavkaza in podatke primerjali z že objavljenimi. Kaže, da obsega zvočni repertoar vrste en sam tip napeva, tj. pozivni napev samca, ki je vrstno specifičen in sestavljen iz dveh vrst fraz. Fraza I se začenja s sosledjem kratkih zvočnih signalov - ehemov, ki jim sledi dolg ehem, fraza II je sestavljena le iz kratkih, pravilno ponavljajočih se ehemov (slika 3a,b). Časovni parametri so prikazani kvalitativno in kvantitativno. Zvočni spekter pozivnega napeva vsebuje dva pasova, enega v območju med 12 in 22 kHz z vrhom med 14 in 18 kHz in včasih stranskim vrhom pri 12 kHz ter drugega, manjšega z vrhom med 7 in 8 kHz. Drugi pas emisije je dobro izražen predvsem na posnetkih, narejenih iz bližine. Primerjava dobljenih podatkov in podatkov iz literature dokazuje, da populacije *C. tibialis* iz Slovenije, Dalmacije (Hrvaška) in južnega Kavkaza tvorijo enotno skupino, ki brez dvoma pripada istemu taksonu, medtem ko imajo živali iz severnega Kavkaza posebnosti tako v zgradbi genitalnega aparata kot tudi v časovnih parametrih napeva. Samci povzročajo med petjem tudi tresljaje podlage. Vibracijska sestavina pozivnega napeva, posneta nekaj decimetrov od škržata, ima v spektru oba frekvenčna vrhova emisije, omenjena že pri zvočnem spektru, približno enako izražena, poleg tega se včasih pojavlja še stranski vrh pri 12 kHz. Čim dlje od živali merimo signale, tem bolj prevladuje le nizkofrekvenčna sestavina vibracijskega napeva okoli 7 do 8 kHz.

Introduction

The loud and to many people annoying sounds of big cicadas (such as *Lyristes plebejus, Cicada orni, Tibicina haematodes*) are an obligate and typical component of the summer Mediterranean soundscape. That is why they are well known and studied in detail (for references see SCHREMMER, 1957; SCHEDL, 1986). Small palaearctic cicadas of the genus *Cicadetta* have recently been subdivided by some taxonomists (Boulard, Schedl; see SCHEDL, 1986) into several genera (*Cicadetta, Cicadivetta* and *Tettigetta*) and placed into different families (Cicadidae and Tibicinidae)[1]. They are much less studied from the standpoint of their biology, ecology, behavior, and especially bioacoustics because of the high-frequency content of their calling songs, barely audible to humans, and inconspicuous coloration. Related cicadas show different adaptations for acoustic communications in markedly different environments (see POPOV, 1981; POPOV & SERGEEVA, 1987), and deserve more attention.

Recently, we used a new bioacoustic method to detect, locate, and record high-fre-

[1] This innovation is not accepted by some taxonomists (personal communication of A.F. Emelyanov).

quency cicadas, which appeared to be effective for tens of meters and allowed us to both count the animals and study their spatial distribution (GOGALA & POPOV, 1995).

During the last few seasons we investigated the sound emissions of cicadas in Slovenia and compared the results with previously investigated populations in parts of the former USSR. One of the starting points was the observation of one of us (M.G.) in 1993 that the species *Cicadetta tibialis* from the Slovenian Karst showed the same song pattern as the *C. caucasica* described by POPOV (1975). This had also been affirmed by JOERMANN and SCHNEIDER in 1987. Therefore, we decided to initiate a series of publications describing and comparing the acoustic behavior of various European Palaearctic populations of singing cicadas with *C. tibialis*.

Material and Methods

Cicadas - *Cicadetta tibialis* (Panzer 1798) (=*Cicadivetta tibialis*: BOULARD, 1982) - were investigated in the warm regions of Slovenia (Karst and seaside) during June and July 1993-95, then compared to animals from Georgia, Azerbaijan, and Chechnya (surroundings of Grozny) studied from the end of June to the beginning of July.

The acoustic recordings in Slovenia were made in the field using digital techniques in the sonic range between 20 and 20000 Hz with SONY DAT-corders TCD D3 and TCD D7 (sampling rate 48 kHz, 16 Bit dynamic range) connected to a TELINGA PRO III parabolic stereo microphone (parabola diameter: 57 cm). All recordings were made during the hot time of day in ambient temperatures between 22 - 42°C.

Sound recordings were visualized as oscillograms after transfer to an ADAP II ATARI ST computer Hard Disk Recording system via the digital interface. Time parameters of the songs were measured from recordings longer than 30 seconds; selected parts were chosen for spectral analyses. These were made on a Macintosh Performa 630 or Power PC 8500 /120 computer using Canary 1.2 or Signalyze 3.0 software.

To record the substrate vibrations caused by the calling male, the animal was put into a small mesh cage at the end of a branch of *Fraxinus ornus*. Two Brüel & Kjaer accelerometers type 4501 were glued onto the bush, one to the branch, the second to the main stem at distances of 30 and 130 cm from the cage and then connected with a B&K 2635 preamplifier and a SONY WM D6C cassette recorder. Vibrational signals were processed as sound signals.

The equipment for acoustic recordings and analysis used in the Caucasus has been described in detail in the paper by Popov (1996). Briefly, a tape recorder Nagra IV-SJ, microphones Brüel & Kjaer 4145 or 4135 and a preamplifier B&K 2615 were used, allowing sound recording in the range of 20 - 20000 Hz. Also, some recordings were made with a Reporter-3 tape recorder and MD-63 electret microphone in the range of 200 - 16000 Hz.

The Statview 4.5 program was used for graphic presentation and statistical evaluation of temporal parameters.

The voucher specimens of cicadas from Slovenia are preserved in the collection of the Slovene Museum of Natural History in Ljubljana; the specimens from the Caucasus are in the collection of the Zoological Museum in St.Petersburg, Russia.

Macrophotographs were made with a WILD M8 stereomicroscope with Photoautomat.

The camera lucida drawings of the genitalia were made by A. F. Emelyanov.

Results

Cicadas of the species *Cicadetta tibialis* (Panzer, 1798) (Fig. 1) had already been reported from the southwestern part of Slovenia by SCHEDL (1986). He also confirmed the determination of our specimens found in the Slovenian Karst and near the Adriatic coast during June and July 1994. Typical traits were: size and proportions as described by SCHEDL (1986), orange colour of the wing base, red-brown edges of abdominal tergites, lack of anchor shaped pattern on hind wings, and a typical venation, again as described in SCHEDL (1986), but which was not very stable and sometimes differed even on both tegmina or wings of the same animal.

Animals from the Caucasus region had been previously identified as *Cicadetta caucasica* Kol. Nevertheless, there are no clear morphological differences between these when compared to specimens from Slovenia, the only exception being animals from Grozny which differed slightly in the morphology of the genital organs as recently reported by EMELYANOV (1996) and presented in Fig. 2. Therefore, we assumed the same identity for all populations, but investigated the song parameters separately in search of possible consistent differences.

In Slovenia and the Caucasus the singing males and females were usually found on bushes and small trees (*Fraxinus ornus, Acer campestre, Sorbus* sp., etc.), but in some places such as Belvedere (Slovenian coast) they were also regularly found singing in meadows, fields of alfalfa, and on other green plants. In this latter locality the bushes were occupied predominantly by another species, *Tettigetta brullei*, which has a calling song with a similar spectrum. Males sing during the entire day when the weather is fine and ambient temperatures are not too low (above 20°C). The males chirp their calling song from one spot - a small branch or leaf - for a minute or some minutes, then fly, find another position, and start again.

During our investigations in the field, we were able to detect and record only the calling song of this species, produced by solitary males, although we could not exclude the presence of other signals in different contexts, as when animals were at a close range. That is why we made several attempts to imitate some possible contexts by putting several males or males and females in one cage. No other specific sounds which could be interpreted as aggressive or courtship songs were detected in these few tests. However, such experiments should be continued to reach a final conclusion about the sound repertoire of the species, as we used females caught in the field and were not sure they were virgin. Once, while recording in a field inhabited by this species, one of us heard a series of short unusual sounds following a normal song of *C. tibialis*, but we could not find the animal which produced it.

The calling song normally contained two types of phrases (Fig. 3). A sequence of type I could continue for minutes, then the animal suddenly switched to a phrase II, which could last just a few or tens of seconds, then phrase I reappeared. Many times we observed that males stopped singing after phrase II and flew away.

The species-specific structure of phrase I was easily recognisable. It started with a series of short echemes, varying in number between 2 and 15, followed by a long echeme (Fig. 3a). Usually, groups of short phrases I with 2-5 short echemes were separated by longer phrases I with a higher number of short echemes, but there was little regularity to this pattern. As a consequence, the statistical distribution of phrase I duration did not follow a Gaussian but rather a Poisson´s distribution (Fig. 3d). The duration of long (T1) and short (T3) echemes followed a more or less normal Gaussian distribution (Fig 4). We did not find any statistically relevant differences in the long echeme duration in the songs of cicadas from Slovenia and the South Caucasus, but there was a statistically significant difference ($p < 0.001$, paired t-test) between the T1 values in the songs of animals from Chechnya (Grozny surroundings) and all other animals. The same difference was also evident in scattergrams combining the T1/T2 and T3/T5 mean values. The values of these parameters for single animals from Slovenia (11) and the S. Caucasus (5) belonged to the same cluster, and those from Grozny (3) differed slightly.

Usually, the duration and intervals of the last 2-5 short echemes preceding the long echeme in phrases I gradually shortened to 82% and 50% of the first few values, respectively. This trait was more profoundly expressed in the songs of animals from Grozny where the respective values were 58% and 30%. The first interval following the long echeme in phrase I (T6) was shorter in most animals, 103±19 ms, than the ones following (T5), 119±26; these are means from 11 Slovenian animals. In contrast to this, T6 values of three animals from Grozny were significantly higher than T5.

Phrase II structure was simpler in all populations. It consisted of regularly repeated short echemes (Fig. 3b). In the songs of animals from Slovenia and the South Caucasus their duration (T8) was slightly longer than in phrases I (Figs. 4d; 5a,b). With animals from Grozny the picture was more complicated since the distribution of this parameter was bimodal, and the T8 values were mostly either longer or shorter than those in the songs of males from Slovenia and the S. Caucasus (Fig. 5c). Intervals between the echemes of phrase II were longer in all animals than those between the short echemes of phrase I (Figs. 4d,f 5d-f), that is, the echeme repetition rate was a bit slower.

A comparison of the distribution of T9 values in the songs of animals from different populations revealed statistically significant ($p<0,0001$) difference between South Caucasian and North Caucasian (Grozny) populations, whereas the Slovenian population was in between. Nevertheless, more animals from this region should be investigated. If just the mean T8 and T9 values of single animals are compared, data from the songs of all animals form one cluster (Fig. 5g).

The internal organization of long and short echemes is determined by the mode of action of the timbals. As a result of inward buckling due to the single timbal muscle contraction and a passive return to the original state, each timbal produces 2 nearly equally short, 0.8-1.2 ms sound pulses, an in and an out buckling pulse for the single contraction/relaxation cycle of each tymbal muscle (for details see Popov 1975). The two timbals work alternately with a phase shift of 1.0 - 1.8 ms. Their paired single actions gives a group of 4 such pulses (cf. Pringle 1954, Weber et al. 1987, Young &

JOSEPHSON 1983). During production of the short echemes in phrases I and II, timbals work continuously with a rate of about 130 - 170 Hz, and these "fours" follow each other uninterruptedly, forming a more or less regular sequence of pulses with a mean repetition rate of about 530 - 680 Hz (Figs. 6e,7d). The beginning and the end of the long echemes are organized in a similar manner but in its middle part the timbals start to produce a sequence of cycle doublets, each giving a group of 8 single pulses. These "eights" are separated by longer intervals of about 3.8 ms. Thus, the inner part of the long echemes has a clear second order rhythmic structure (Fig. 6d). The mean repetition rate of "eights" is about 63 Hz.

The spectral characteristics of both phrase I and II are very similar. Their frequency spectrum has 2 bands: a main, rather broad, 12 - 22 kHz band with a maximum between 14 - 18 kHz in individual animals, sometimes with a smaller additional peak between 12 and 14 kHz, and a second band with a maximum around 7 - 8 kHz (Figs. 6 - 8). The respective bands are clearly seen on the spectrograms and sonograms (Figs. 6a,b, 7a,b 8a-c). The relative amplitude of the low-frequency peak is dependent on the distance from the singing male. It is better pronounced in recordings at a close range of a few decimeters (cf. POPOV et al. 1985, POPOV et al. 1991).

On one occasion we observed and documented a sudden shift in the main high-frequency peak and a disappearance of the secondary peak at 13.5 kHz in the song of a single animal (Fig. 8). The mechanism of such modulations is not known. Apparently, the animal can control the state of its resonating structures (cf. YOUNG & HILL, 1977). The third peak at 12 - 14 kHz is also present in some vibration recordings (Fig. 9) and can therefore not be an artifact.

Due to the high-frequency spectrum of the song of *Cicadetta tibialis* it is difficult, except for young people, to hear the animals from long distances. Therefore a sensitive directional microphone or even a bat (ultrasonic) detector can be of great help to detect, locate, and recognize the animals in studies of their spatial distribution, ecology, and behavior (GOGALA & POPOV, 1995).

While calling, males produce strong substrate vibrations. The vibration component of a calling song at a close range of 30 cm has the same time pattern as the air-borne sound component, but its 2 to 3 spectral peaks have nearly the same amplitude and the recordings are rather noisy because of wind and other disturbances (Fig. 9a-c). The signals are still distinguishable even at a 1.30 m distance, especially in a certain frequency window. High-frequency song vibrations are much more attenuated during their propagation along the stem. Therefore, at a 1.3 m distance only the frequencies around 5 - 7 kHz still represent the song pattern (Fig. 9b).

The samples of the songs in SUN format (*.au) and the pictures of this and other cicadas from Slovenia are available in the World Wide Web at the address:

http://stenar.arnes.si/guest/ljprirodm3/cikade.html

Discussion

From our analysis of song parameters and comparisons with the previously published data of POPOV (1975) and JOERMANN & SCHNEIDER (1987) it is evident that the sound emissions of *Cicadetta tibialis* from Slovenia, Dalmatia, and the Southern Caucasus do not differ substantially. Probably all these populations belong to the same taxon. It has also become clear that the previous identification of animals from the Caucasus region as a separate species, *Cicadetta caucasica* Kol., was not correct (see recent papers of EMELYANOV, 1996 and POPOV, 1996). On the other hand, the population of *Cicadetta tibialis* from the northern side of the Caucasus shows slight morphological pecularities such as the form of the genital capsule and also differences in temporal song parameters. It is interesting that the songs of the N. Caucasian and S. Caucasian populations differ in such temporal parameters as T5 and T9 much more than any of them from the songs of Slovenian populations. We are aware, of course, that the number of recorded animals from the Grozny surroundings is very small, only three, and they should be studied in the future on a larger scale.

As already mentioned in Materials and Methods, we analyzed recordings made in a wide range of ambient temperatures and pooled the data. This could have influenced the shape of the time distributions as presented in Results. We made this because, contrary to the situation with planthoppers (VRIJER, 1984) and crickets (numerous references in the book by HUBER et al., 1989), we did not find any significant influence of temperature on the basic time parameters of the calling song in *C. tibialis*. For example, animal No.1 was recorded at 39°C and animal No. 4 at 29°C (both from the S. Caucasus). Despite a 10°C difference in ambient temperatures, the critical parameters T1, T5, and T9 were: 289±31 and 293±43 ms; 99±15 and 101±9 ms; 121±10 and 118±11 ms, respectively. Without any statistical procedures one can see that there are no significant differences between these values. It may well be that the body temperature of these small insects while singing is determined more by timbal muscle activity than by ambient temperature. This problem also needs further investigation.

The spatial distribution of *C. tibialis* males was easily studied with directional microphones. Therefore, we can confirm the description of SCHEDL (1986) that these cicadas usually sit and sing on small bushes, very often also on higher shrubs or small trees some meters above the ground. We mentioned the special case of Belvedere (south of Izola, Slovenia) where these animals can be regularly found singing on alfalfa plants and other small vegetations such as potatoes, beans, etc. It can well be that in this case *C. tibialis* was pushed to an unusual habitat by another very abundant species, *Tettigetta brullei*. A similar situation we observed on the island Krk in Croatia.

Contrary to SCHEDL (1986), in studying the cicada activity period we recorded some singing animals in the Karst region (Brje near Komen, Slovenia) as late as in the first week of August, but could not find them before June.

In subsequent papers we will show that with acoustic methods it is easy or at least easier to distinguish between species of singing cicadas than by using morphology alone. Of course, with these methods only the presence, location, and identification of males can be accomplished. But females can for obvious reasons often be found in the vicinity of males. Therefore, these methods can and should be used more frequently in faunistic and ecologic surveys.

Acknowledgements

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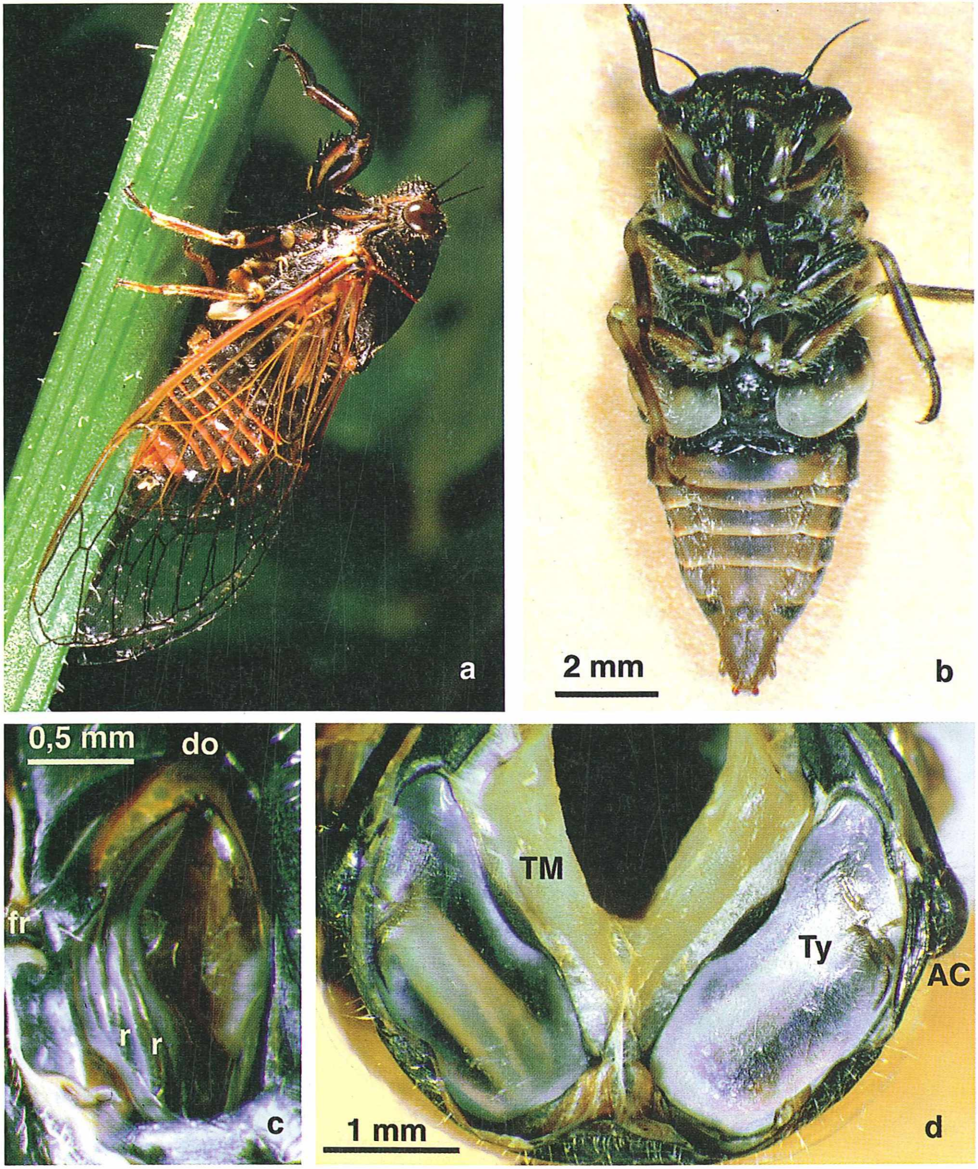

Fig. 1: a) *Cicadetta tibialis*, male, b) ventral view with opercula, c) left timbal with two long ribs on the proximal field (do = dorsal, fr = frontal), d) tympanal membranes Ty and timbal muscles TM - as seen caudally after the abdomen is removed; AC - auditory capsule, T1, T2 - timbal ribs (for morphology details see reviews: Pringle, 1954; Weber et al., 1987; Young & Hill, 1977; Young & Josephson, 1983; Popov 1975, 1985; Popov et al., 1991).

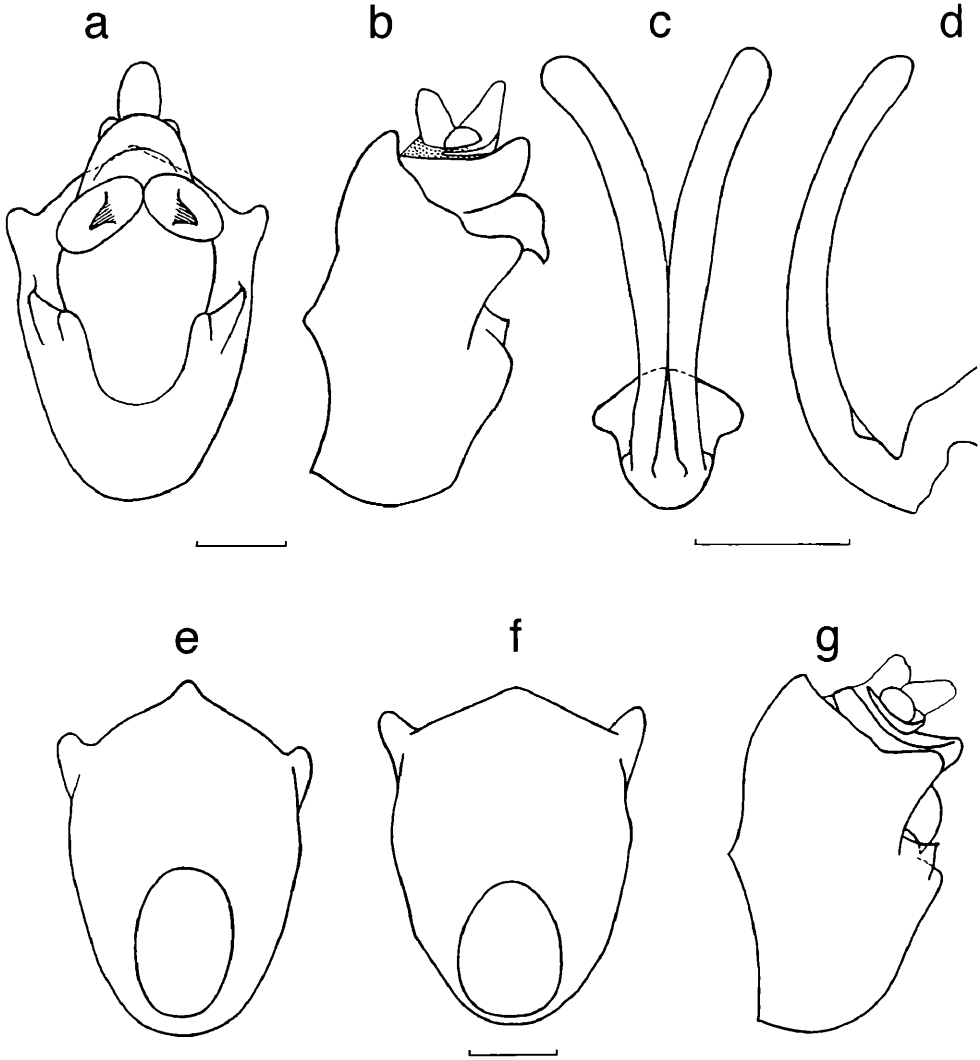

Fig. 2: Outer genital organs of *Cicadetta tibialis* male: a) pygophor and anal tube from behind, b) pygophor from the left, c) penis from behind, d) penis from the left, e) pygophor - front view (Georgia), f) pygophor - front view (Grozny), g) pygophor and anal tube from the left (Grozny). Calibration: 0.5 mm. Courtesy of A.F. Emelyanov.

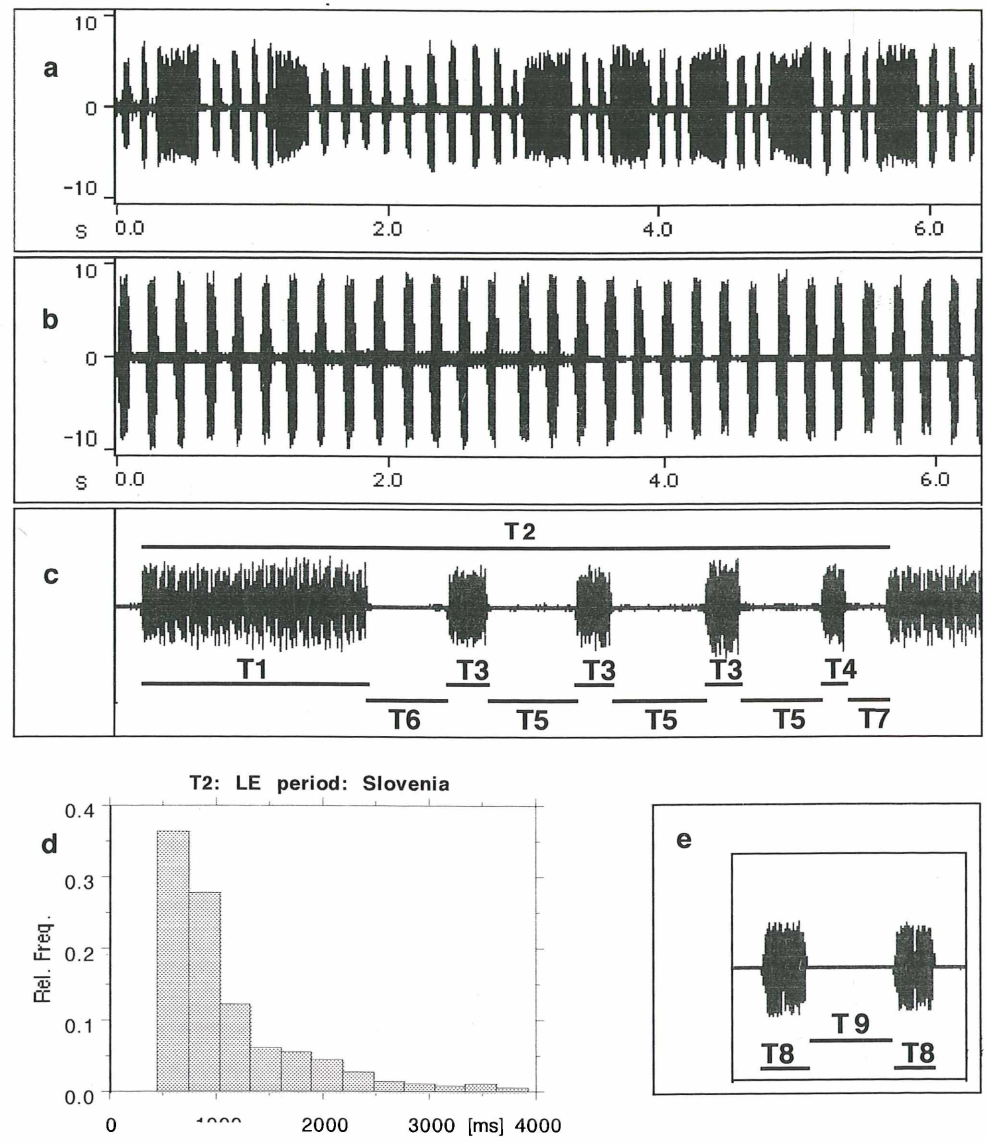

Fig. 3: Oscillograms of the calling song of *Cicadetta tibialis*: a) sequence of type I phrases, with the selection >c<; b) phrase II; c) selection >c< expanded and schematic presentation of temporal parameters used in our analysis of phrase I: T1 = long echeme duration, T2 = repetition period of phrase I, T3 = short echeme duration, T4 = duration of the last short echeme in a phrase, T5 = interval between short echemes, T6 = interval between long and first short echeme in a phrase, T7 = interval between the last short echeme preceding the long echeme; d) histogram of the phrase I repetition period (T2) in the songs of 11 animals from Slovenia (N=408); e) phrase II: T8 = echeme duration, T9 = interval between echemes.

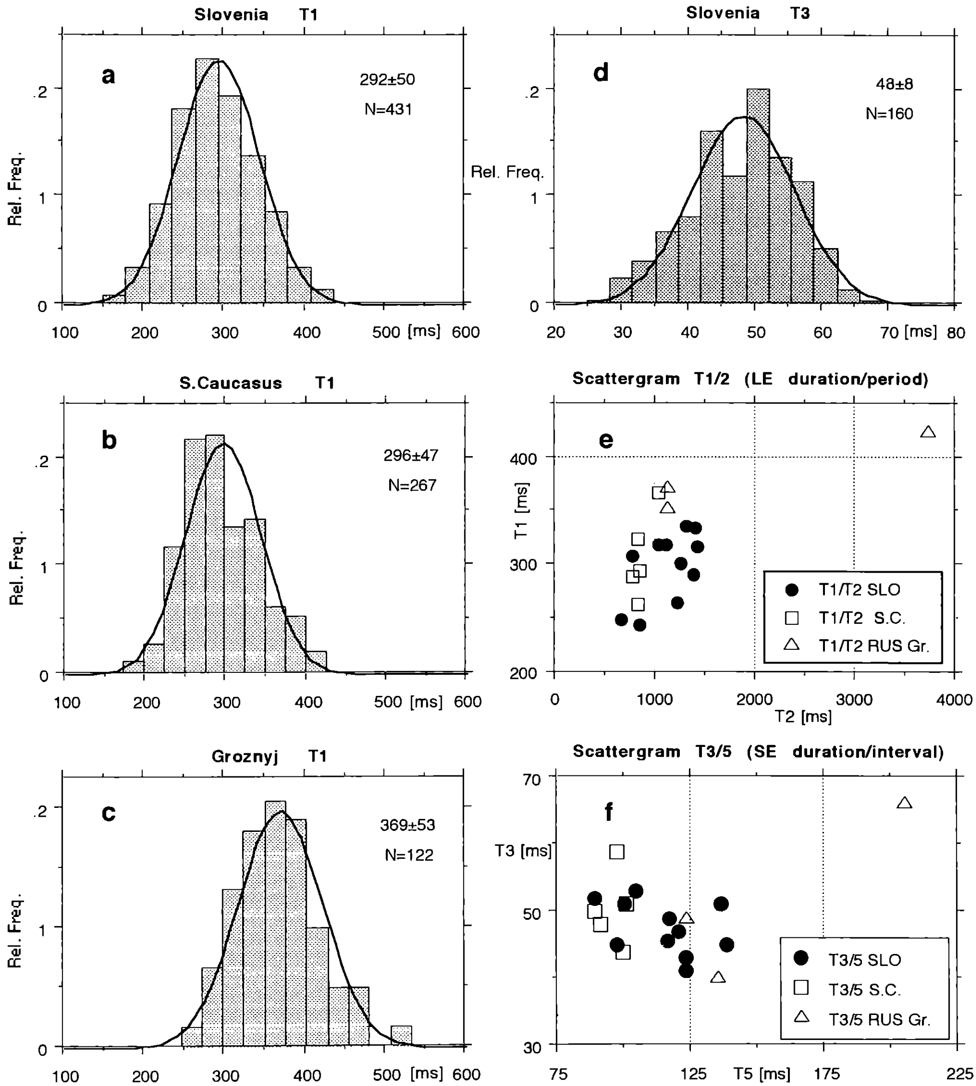

Fig. 4: Temporal parameters of the calling song of *Cicadetta tibialis* - phrase I: a-d) histograms with normal distribution curves, means ± standard deviation and numbers (N) of long echeme duration (T1) in the songs of 11 animals from Slovenia (a), 5 animals from the South Caucasus (b) and 3 animals from Grozny (c) and d) distribution of short echeme duration (T3) in the songs of animals from Slovenia; e and f) scattergrams of long echeme (LE) duration across repetition period (e), and short echeme (SE) duration across interval (f) for cicadas from Slovenia (SLO), the S. Caucasus (S.C.) and Grozny (RUS Gr.), mean values for each animal are presented.

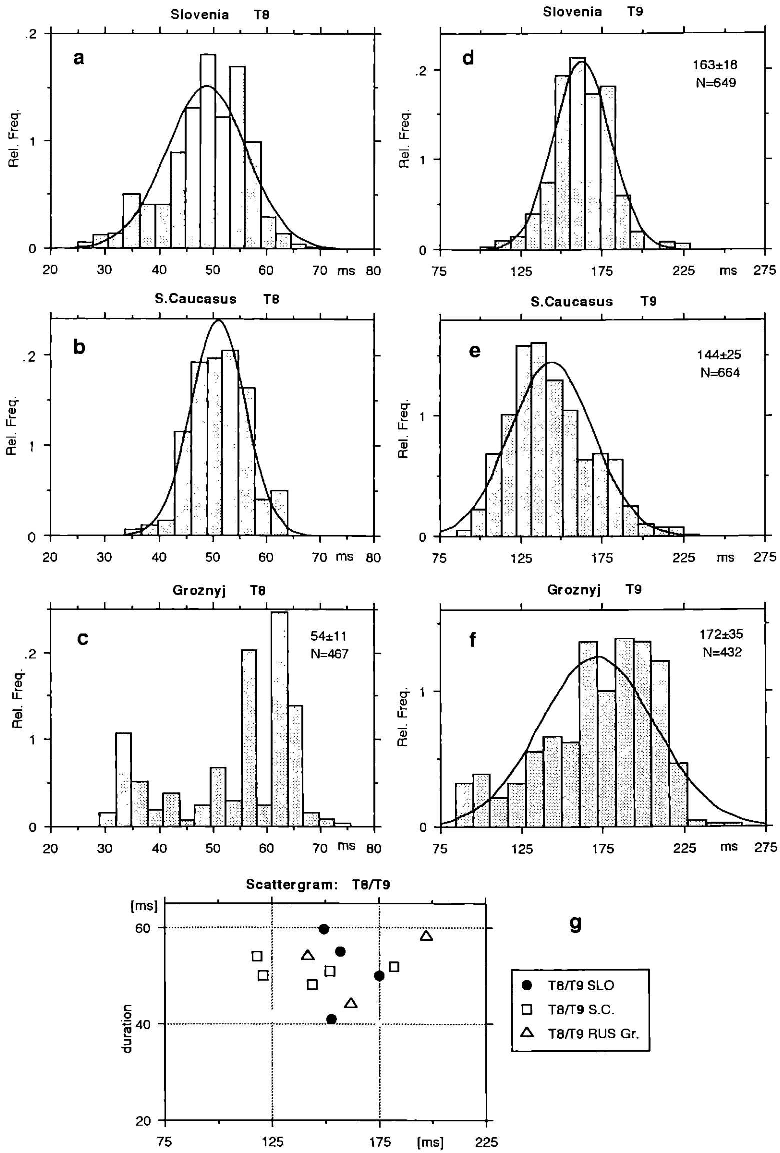

Fig. 5: Temporal parameters of the calling song of *Cicadetta tibialis* - phrase II: a-f) histograms with normal distribution curves, means ± standard deviation and number (N) of echeme durations (T8: a-c) and intervals (T9: d-f) in the songs of 4 animals from Slovenia (a, d), 5 animals from the South Caucasus (b, e) and 3 animals from Grozny (c, f); g) scattergram of echeme duration across the interval (T8/T9) for cicadas from Slovenia (SLO), the S. Caucasus (S.C.) and Grozny (RUS Gr.); mean values for each animal are presented.

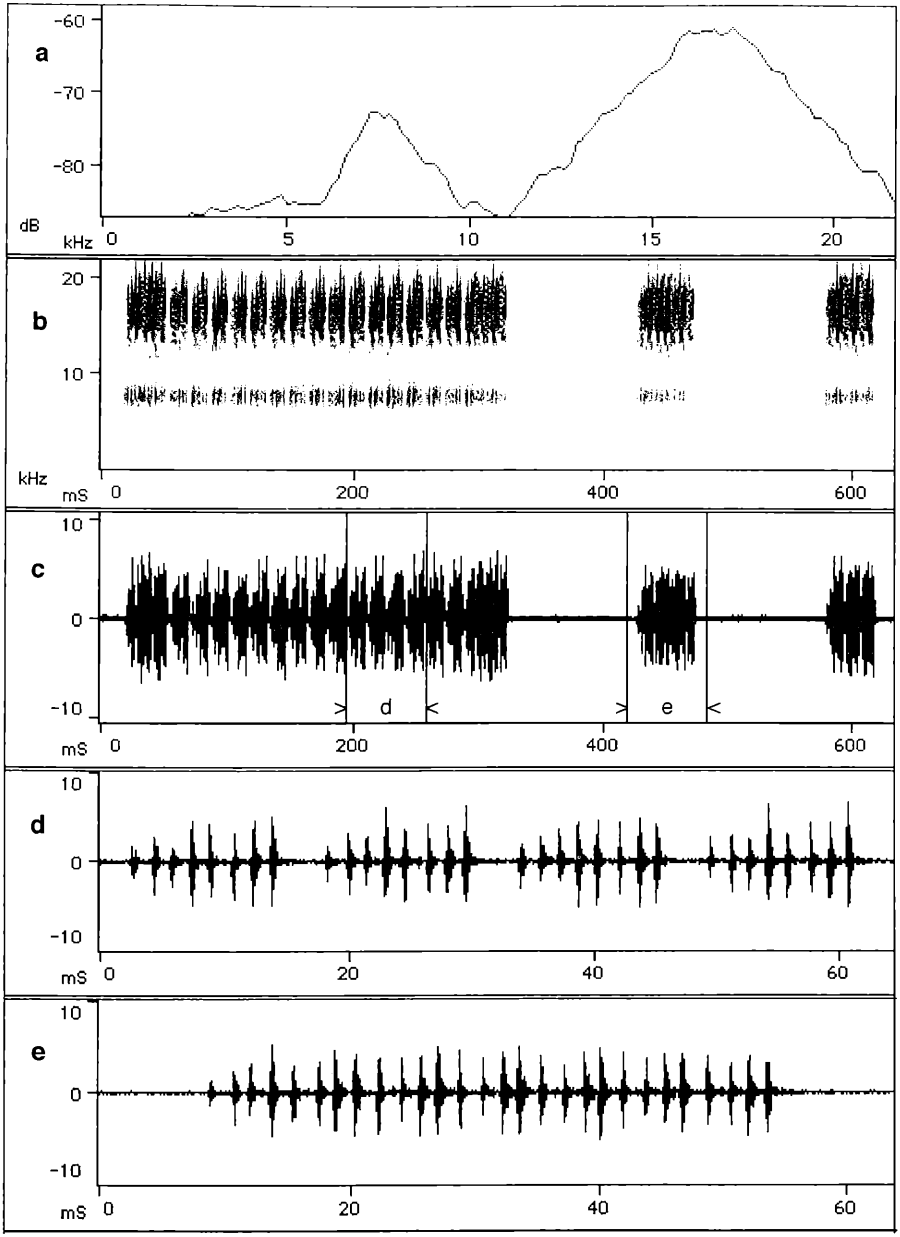

Fig. 6: Spectral characteristics and pulse structure of echemes in phrase I of the calling song: a) frequency spectrum, b) sonogram and c) oscillogram of the same part of the phrase I, d) pulse structure of a selected part of a long echeme (c: >d<) - note groups of eight pulses, e) pulse structure of the selected short echeme (c: >e<) - note the repeated pattern of four pulses (Canary 1.2).

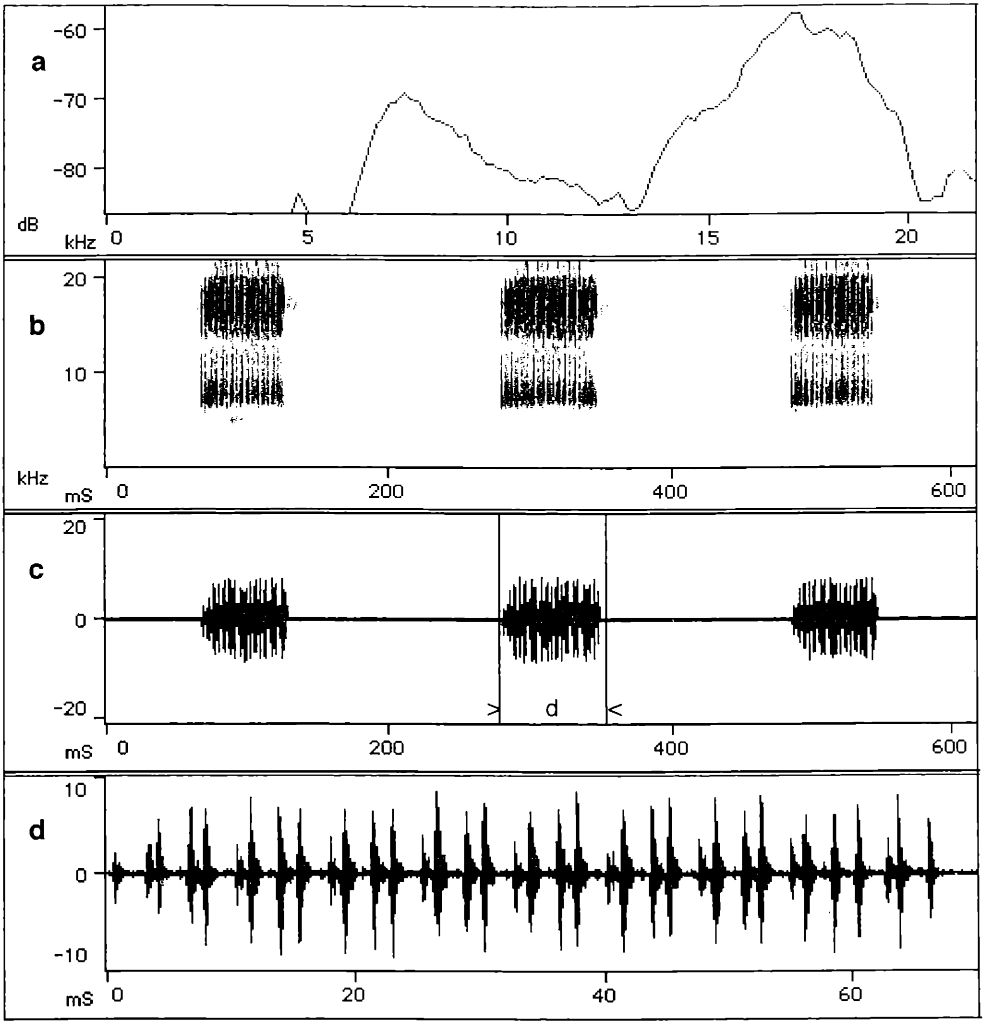

Fig. 7: Spectral characteristics and pulse structure of echemes in phrase II of the calling song: a) frequency spectrum, b) sonogram and c) oscillogram of the same part of a phrase II, d) pulse structure of the selected echeme (c: >d<) - again a repeated pattern of four pulses is evident. (Canary 1.2).

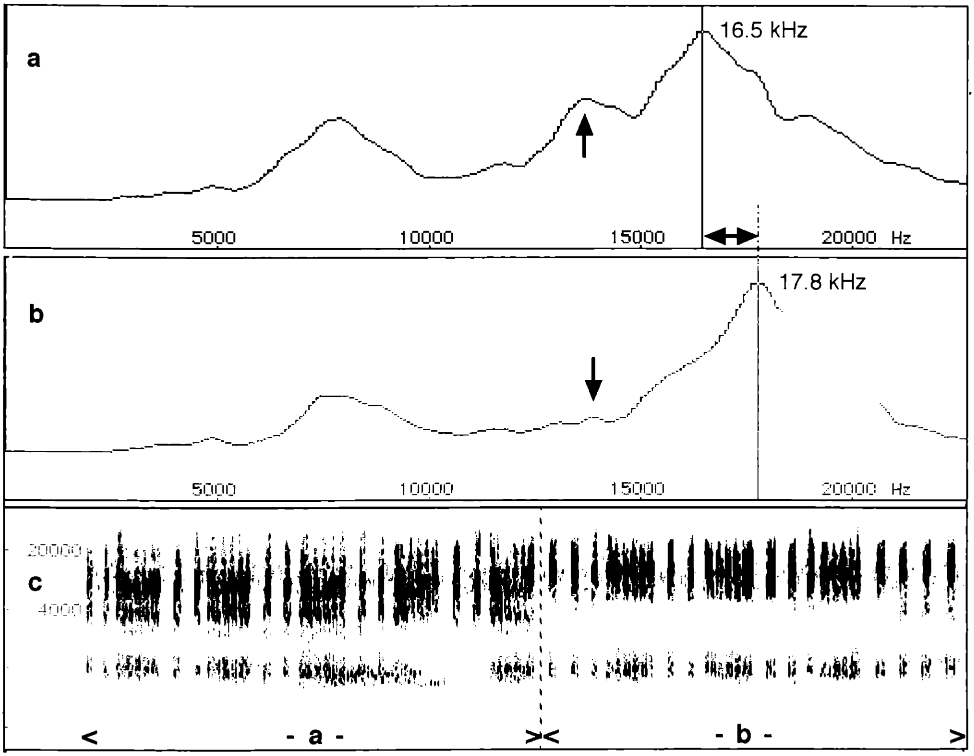

Fig. 8: A sudden spectral change in the song of a single animal. a) and b) frequency spectrum of a first (left of the dotted line in c and d) and second part (right of the line) of a song shown in sonogram (c) and oscillogram (d). In a), arrow shows a secondary frequency peak present during this recording for many tens of seconds, which suddenly disappeared at the moment indicated by the dotted line; simultaneously the main frequency maximum shifted from 16.4 kHz to 17.9 kHz (Signalyze 3.1).

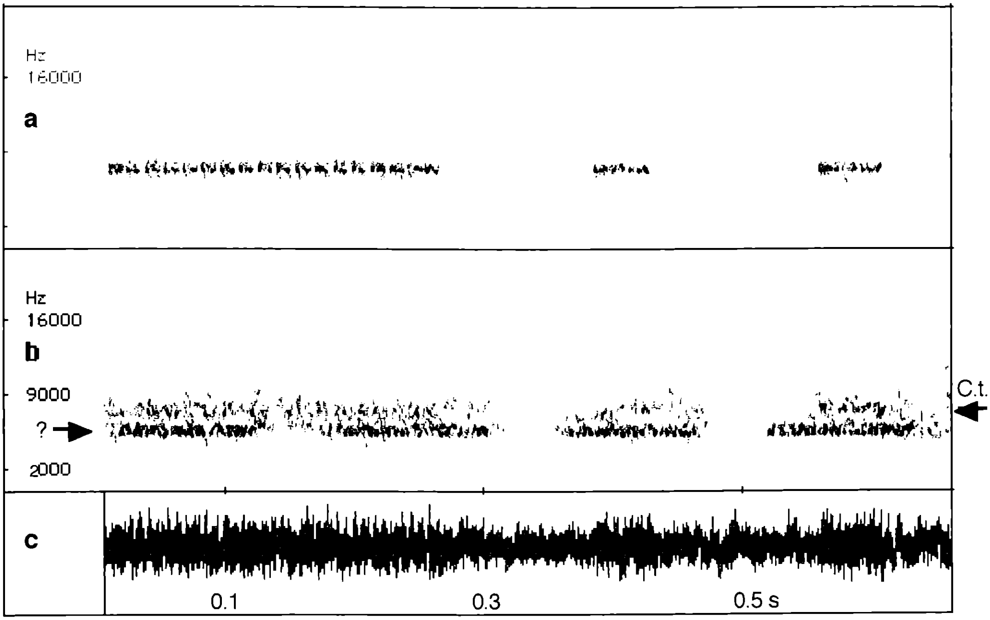

Fig. 9: Vibrational component of the calling song (phrase I) of *Cicadetta tibialis*: a, b) sonograms of the vibration signals (accelleration) recorded at 30 cm (a) and 130 cm (b) from the singing animal on a *Fraxinus ornus* branch; in b) the sonogram is dominated by the vibration song of another animal (? arrow), possibly a bug, but a faint *C. tibialis* pattern (C.t. arrow) can still be seen; c) oscillogram of the same selection at a distance of 30 cm (Canary 1.2).

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