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The pulse-train calls of male *Zhangixalus faritsalhadii* Gonggoli et al. 2024

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Zhangixalus faritsalhadii Gonggoli et al., 2024, is a was recently described from Central Java, Indonesia. This species is characterised by snout–vent lengths of 37.6–40.7 mm in males and 50.7–54.5 mm in females, and males have calls composed of pulses with irregular intervals (Gonggoli et al., 2024). In comparison, other *Zhangixalus* species such as, *Z. dulitensis* from Brunei and *Z. achantharrhena* from West Sumatra, Indonesia emit calls consisting of notes containing three pulses, while *Z. prominanus* from Pahang Malaysia emits notes with 6–17 pulses (Ibnudarda et al., 2025). Male *Z. jodiae* from northern Vietnam, emit advertisement calls comprising six notes (Nguyen et al., 2020) while male *Z. melanoleucus* from northeast Laos, generates clicking notes, each with 2–3 pulses (Brakels et al., 2023).

East Asian species show a high variation in call behaviour. For instance, the male *Z. dugritei* from Sichuan, China, emits calls with 2–14 pulses (Matsui and Wu, 1994), whilst male *Z. dennysi* from Hainan, China, emits advertisement calls with 3–5 notes (Wang et al., 2012). Furthermore, the advertisement calls of *Z. zhoukaiya* from Anhui, China, consist of 10–25 notes, and note lengths and intervals also vary among calls (Fang et al., 2018). Male *Z. prasinatus* from Taiwan exhibit three distinct note types: A (6–9 pulses), B (3–12 pulses), and C (one pulse) (Cheng et al., 2022). In *Z. lishuiensis* from Zhejiang Province, China, male advertisement calls exhibit a hierarchical structure composed of three note types (Hao et al., 2025). In light of these unique vocalisations, a re-examination of the calling behaviours of male *Z. faritsalhadii* is warranted. Such an investigation may yield valuable insights into the diversity of vocal behaviours within the genus *Zhangixalus*.

Calls of male *Z. faritsalhadii* were recorded on 5 and 6 March 2025 during the wet season, at the type locality of the species: Mt. Slamet in Kalipagu, Ketenger Village, Baturaden District, Banyumas Regency, Central Java Province, Indonesia. Advertisement calls from a single individual were recorded at distances of 1–2 metres using an A-Zoom H1N handy recorder and saved as WAV files with a sampling rate of 44.1 kHz and 16-bit resolution. Following the completion of the recordings, the males were captured, and their SVL was measured using a digital calliper with an accuracy of 0.1 mm. The SVL of the male was 36.5 millimetres, and the air temperature near the calling male was 20.2 °C. Based on external morphology and location we identified this frog as *Z. faritsalhadii* (Gonggoli et al., 2024). The irregular dark blotches patterns found on the frogs' dorsal to distinguish between males (Fig. 1E) according to Patel and Das (2020).

We measured multiple call characteristics following the protocols described by Köhler et al. (2017): call duration, silent periods (seconds), pulse numbers, pulse rates (pulses per second), interval between calls (seconds), calls per minute (calls/min), note and pulse duration (milliseconds), internote and interpulse intervals (milliseconds), dominant frequency (Hertz), dominant frequency modulation (Hertz/ms), and peak frequency (Hertz). The coefficients of variation (CV) were calculated from the means and standard deviation of male acoustic parameters, and these properties were categorised according to Gerhardt (1991). Spectral and temporal parameters were analysed using Raven Pro version 1.6 (Centre for Conservation Bioacoustics, 2019) and visualised in RStudio version 2022.12.0+353 with the *seewave* package v2.2.3 and *tuneR* package v1.4.7 (Ligges et al., 2018; Sueur et al., 2008; RStudio

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Team, 2020). Spectrograms were generated using a Hanning window, a Fast Fourier Transform (FFT) size of 256 samples, and an 87.5% overlap. Data are presented as mean ± SD (minimum–maximum).

Three recordings were analysed from a single male, totalling 73.3 ± 18.6 seconds (range: 51.8–84.1 seconds; Fig. 1A; Supplementary Audio, Fig. S1; see https://figshare.com/s/a954159a6091cb010efe). Two distinct call segments were identified. The first was a slow-tempo segment lasting 5.6 ± 3.4 seconds and containing 7.7 ± 3.1 pulse notes. Some sequences contained between 1–3 pulses per note (Fig. 1A; red line). Notes with two pulses were most prevalent (n = 21). On average, this segment comprised 15.3 ± 5.9 pulses (n = 46) at a rate of 2.8 ± 0.7 pulses per second and was separated by silent intervals averaging 863.9 ± 626.7 ms.

The second segment was a pulse-train; it lasted 65.3 ± 15.9 seconds and consisted of 215 ± 42.5 pulse notes (n = 645), with pulse number of 555.7 ± 72.2 pulses (n = 1667) at a rate of 8.7 ± 1.2 pulses per second (Fig. 1A; red line). A gap (pulse-train delayed) of 1.8 ± 1.4 seconds (range: 0.3–3.0 seconds; red arrow) separated these segments (Fig. 1A). Overall, the pulse-train segment exhibited pulse notes containing between 1–9 pulses per note in an irregular sequence, with 2-pulse notes being the most common (n = 402 of 643 pulse notes) and was separated by silent intervals averaging 216.3 ± 106.3 ms.

The overall pulse note had a mean duration of 90.2 ± 37.4 ms (range: 29.1–296 ms; n = 668) and dominant frequency were 1571.5 ± 84.9 Hz. Approximately 373 notes exhibited frequency modulation, with a mean modulation rate of 15.7 ± 6.6 Hz/ms. Most notes demonstrated irregular rise-and-fall time patterns in reaching reached full amplitude within 72.4 ± 51.6 ms and decayed over 57.1± 28.5 ms. Additional dominant frequencies (DF1–DF4) for these pulses were observed at 1563.7 ± 66,4 Hz, 3030.6 ± 203.5 Hz, 4687.1± 223.7 Hz, and 6247.5 ± 203 Hz.

Based on an analysis of the pulse notes, the inter-pulse interval for several notes ranged from 7.5 ± 3.7 ms (range: 1.7–20.4 ms; n = 132 notes). Although the pulse shape remains relatively consistent, males can modify pulse duration in multi-pulse calls. In multi-pulse calls, introductory/first pulse (n = 653; Fig. 1B; red arrow) had a mean duration of 31.6 ± 3.8 ms (range: 8.9–45.5 ms). Secondary pulses (n = 393; Fig. 1D; see asterisks) exhibited a mean duration of 34 ± 3.6 ms (25.2–54.2 ms). The final/last pulses (n = 653; Fig. 1C; red arrow) showed a mean duration of 38.3 ± 6.0 ms (23.4–60.0 ms).

Overall, the coefficients of variation (CV) for spectral and temporal acoustic properties indicate that pulse note duration (CV = 41%), internote interval (CV = 84%), and minimum and maximum frequency (CV = 15%) exhibit substantial variability, with CVs exceeding 12%. In contrast, the dominant frequency (CV = 5.4%) shows moderate variability, defined as greater than 5% but less than 12% (Gerhardt, 1991). Detailed acoustic parameters are presented in supplementary Table S1 and S2.

In conclusion, this study demonstrates that male *Z. faritsalhadii* produce pulse-train calls composed of both single and multi-pulse notes arranged in irregular sequences. Pulse trains exhibit limited variability in static properties but display substantial variability in dynamic spectral and temporal characteristics. Furthermore, they generate modulated pulse notes that vary in pitch or amplitude. These features indicate that pulse-train calls facilitate species recognition and individual identification among males, transmit information regarding mate quality and female directional preferences (Gerhardt, 1991), and enable vibrational communication through the substrate (Márquez et al., 1993).

By modifying call structures male frogs can adjust both the number of pulses per note and the duration of pulses in the introductory or terminal note positions, thereby altering the intervals between notes and the overall pulse train duration. In some species, such interval changes result from interruptions by calls from other males (Martínez-Rivera and Gerhardt, 2008; Schwartz et al., 2010) or calling motivation (Köhler et al., 2017). Additionally, a shorter silent gap may prevent background noise and reverberation from filling the interval as propagation distance increases, although only up to the tolerance limit of females whose temporal structure recognition is compromised (Kuczynski et al., 2010).

Furthermore, the train of pulses in anuran calls result from either active or passive movement of secondary membranes in the larynx or from the sequential production of discrete pulses through active contraction of the body wall muscles (Bosch and De la Riva, 2004; Martin, 1972). Therefore, more research is required to investigate the behaviour of pulse-train calls in male *Z. faritsalhadii*, with particular attention to overlap behaviour (calling strategy), female preference, and laryngeal structure, in order to address unresolved questions identified in this study.

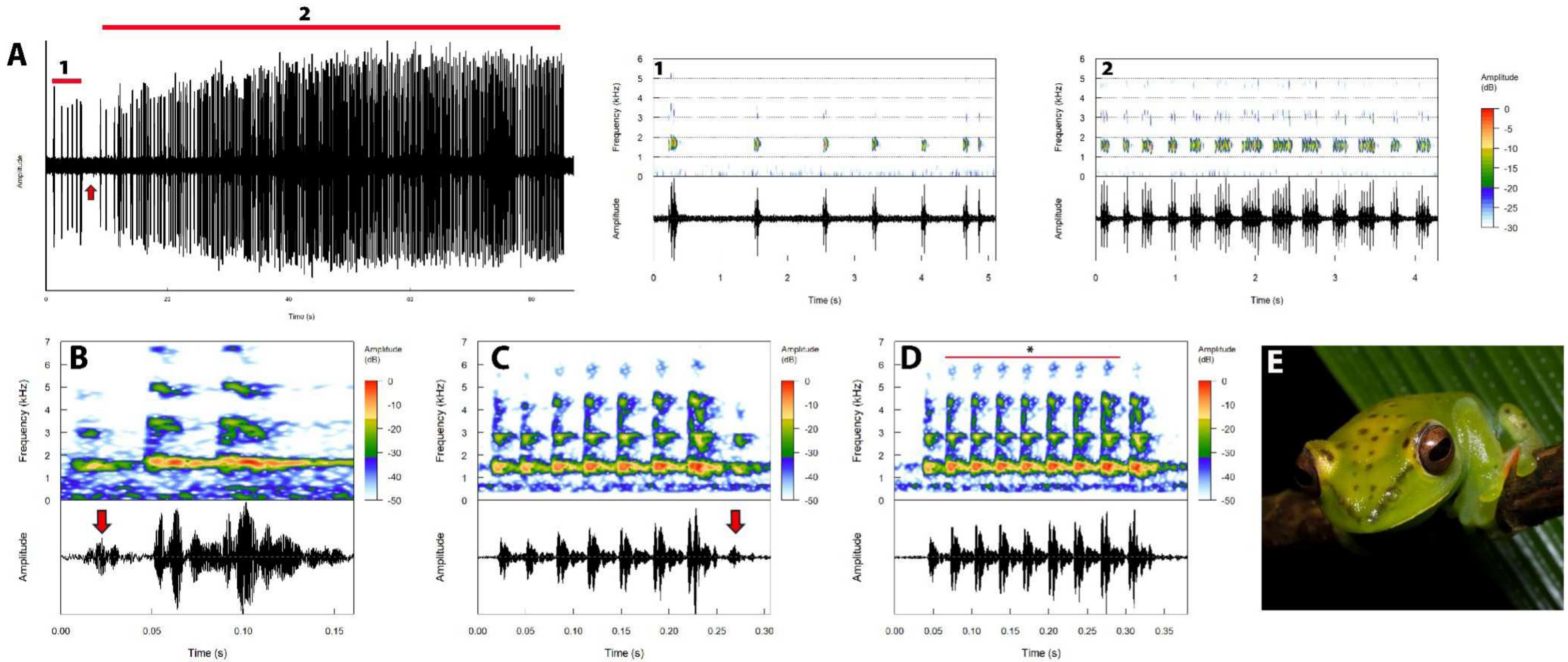

Figure 1. The pulse-train call (A) and notes of male *Zhangixalus faritsalhadii*. (B) Pulses note consist of short introductory pulse (red arrow). (C) Pulses note consist of short last/end pulse (red arrow). (D) Pulse notes consist of nine pulses. (E) Male *Zhangixalus faritsalhadii*. Spectrograms are shown above and oscillograms below. * = sequence of secondary pulses, 1 = The initial segment (read line), and 2 = The pulse-train segment (red line). Photo by Misbahul Munir.

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