# Temporal organization of golden jackal (*Canis aureus*, L. 1758) howling near a rural settlement: event-level evidence from passive acoustic monitoring

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**Abstract:**
The golden jackal (*Canis aureus*) is an ecologically adaptable social canid whose long-distance vocal behaviour remains insufficiently described under natural conditions, particularly in human-modified landscapes. This study examined the temporal and acoustic organisation of evening golden jackal howling recorded from a fixed location near a rural settlement in southeastern Bulgaria. Eight stereo recordings, probably representing repeated vocal activity of the same local social group, were analysed in Raven Pro using a standardised frequency range of 150-5000 Hz. A total of 65 individual vocal events and 57 inter-event intervals were identified. Vocal events had a median duration of 1.76 s (interquartile range: 1.26-2.21 s), whereas inter-event intervals had a median duration of 0.78 s (0.41-1.54 s). Vocal events were significantly longer than the intervals that separate them (Mann-Whitney $U = 2780.5$, $p < 0.001$, Cliff's $\delta = 0.501$), and 63.2% of all inter-event intervals were shorter than 1 s. No significant associations were detected between event duration and frequency 5%, centre frequency, frequency 95%, 90% bandwidth, peak frequency, aggregate entropy or average entropy after false-discovery-rate correction. Sequential analyses revealed significant positive associations between event duration and the following interval, between interval duration and the following event, and between the durations of consecutive events. These findings indicate that the recorded howling was organised into temporally coherent sequences rather than isolated acoustic emissions. The results provide event-level evidence of structured vocal timing in a free-ranging local golden jackal group and demonstrate the value of passive acoustic analysis for studying canid communication near human settlements. Because the recordings originated from one location and probably involved the same social group, the findings should be interpreted as a description of within-group vocal organisation rather than population-level variation.

**Keywords:** *Canis aureus*, acoustic communication, vocal sequences, inter-event intervals, southeastern Bulgaria.

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## Abstract

The golden jackal (*Canis aureus*) is an ecologically adaptable social canid whose long-distance vocal behaviour remains insufficiently described under natural conditions, particularly in human-modified landscapes. This study examined the temporal and acoustic organisation of evening golden jackal howling recorded from a fixed location near a rural settlement in southeastern Bulgaria. Eight stereo recordings, probably representing repeated vocal activity of the same local social group, were analysed in Raven Pro using a standardised frequency range of 150-5000 Hz. A total of 65 individual vocal events and 57 inter-event intervals were identified. Vocal events had a median duration of 1.76 s (interquartile range: 1.26-2.21 s), whereas inter-event intervals had a median duration of 0.78 s (0.41-1.54 s). Vocal events were significantly longer than the intervals that separate them (Mann-Whitney $U = 2780.5$, $p < 0.001$, Cliff's $\delta = 0.501$), and 63.2% of all inter-event intervals were shorter than 1 s. No significant associations were detected between event duration and frequency 5%, centre frequency, frequency 95%, 90% bandwidth, peak frequency, aggregate entropy or average entropy after false-discovery-rate correction. Sequential analyses revealed significant positive associations between event duration and the following interval, between interval duration and the following event, and between the durations of consecutive events. These findings indicate that the recorded howling was organised into temporally coherent sequences rather than isolated acoustic emissions. The results provide event-level evidence of structured vocal timing in a free-ranging local golden jackal group and demonstrate the value of passive acoustic analysis for studying canid communication near human settlements. Because the recordings originated from one location and probably involved the same social group, the findings should be interpreted as a description of within-group vocal organisation rather than population-level variation.

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## Introduction

The golden jackal (*Canis aureus*, L. 1758) is a medium-sized social canid widely distributed across Eurasia and is characterised by ecological, behavioural and social flexibility. This species occupies a broad range of natural and human-modified environments, including agricultural landscapes, rural settlements and habitat mosaics in which food resources and shelter occur in close proximity to human activity (Moehlman and Hayssen 2018, Sillero-Zubiri et al. 2004, Macdonald 1979). During recent decades, the European distribution of the golden jackal has expanded considerably beyond its historical strongholds in southeastern Europe (Acosta-Pankov 2018, Trouwborst et al. 2015). This expansion has been associated with several interacting ecological and anthropogenic factors, including landscape transformation, resource availability and changes in the distribution of larger carnivores (Krofel et al. 2017, Giannatos et al. 2005). Golden jackals commonly live as territorial pairs or family groups, although group composition and social organisation may vary according to reproductive status, resource distribution and local ecological conditions (Pecorella et al. 2023, Moehlman and Hayssen 2018, Macdonald 1979). Camera-trap observations of a free-ranging family group have demonstrated that relatively stable groups may consist of a dominant breeding pair and one or more generations of offspring (Custers et al. 2024). Vocal communication is expected to be particularly important in such social systems because it permits animals to exchange information over distances that exceed the range of visual contact (Smith et al. 2025, Graf and Hatlauf 2021, Jaeger et al. 1996) Long-distance howling is one of the most conspicuous components of communication in social canids. It may contribute to territorial advertisement, spatial separation between neighbouring groups, reunion of separated group members and

maintenance of social cohesion (Harrington and Mech 1983, 1979, Theberge and Falls 1967). In golden jackals, playback studies have supported a role of howling in passive territory maintenance and mutual avoidance between neighbouring groups (Jaeger et al. 1996). Howling responses also show seasonal variation in Eastern Bulgaria, indicating that vocal activity is influenced by the annual social and reproductive cycle (Acosta-Pankov et al. 2018). More recent stationary observations of a non-captive family group have further expanded the known repertoire of long- and short-range golden jackal vocalizations and emphasised the diversity of their possible social contexts (Konstantinov et al. 2025).

Canids possess structurally diverse vocal repertoires, and their long-distance calls vary in duration, frequency modulation, harmonic composition and temporal organisation (Cohen and Fox 1976, Tembrock 1976). Social canids may possess structurally complex vocal repertoires composed of low-frequency, high-frequency and pulsed acoustic components, as shown in detailed spectrographic studies of the dhole (*Cuon alpinus*) (Volodin et al. 2001). Comparative studies have shown that acoustic properties of howls may contain information related to species, subspecies, individual identity or social-group membership (Suter et al. 2017, Kershenbaum et al. 2016, Root-Gutteridge et al. 2014, Zaccaroni et al. 2012, Palacios et al. 2007, Tooze et al. 1990). However, most detailed quantitative studies of canid howling have focused on wolves, whereas the spontaneous vocal behaviour of free-ranging golden jackals remains comparatively understudied.

Bioacoustic techniques provide a non-invasive method of detecting and studying free-ranging canids in situations where visual observation is difficult. Both playback surveys and passive acoustic monitoring have been successfully applied to golden jackals (Acosta-Pankov et al. 2018, Comazzi et al. 2016, Giannatos et al. 2005). Spectrographic analyses can reveal the temporal and frequency structure of individual and group vocalizations, while arrays of autonomous recorders can support spatial localisation of calling animals (Smith et al. 2025, Graf and Hatlauf 2021). Nevertheless, signal attenuation, unknown caller distance, environmental noise and the inability to identify individual callers remain important limitations of fixed-point field recordings.

Detailed information is particularly scarce regarding the event-level temporal organisation of spontaneous golden jackal howling near human settlements. Previous studies have concentrated primarily on presence-absence detection, playback responses, chorus composition or acoustic localisation, whereas the relationships among consecutive vocal events and the intervals separating them have received less attention. Examining these relationships may reveal whether vocal elements are emitted independently or form structured temporal sequences.

The present study therefore investigated the acoustic and temporal organisation of evening golden jackal howling recorded from a fixed location near a rural settlement in southeastern Bulgaria. Individual vocal events and the inter-event intervals separating them were identified using spectro-temporal criteria. The study aimed to describe the duration and acoustic-energy characteristics of the vocal events; to compare the duration of vocal events with that of inter-event intervals; to test whether event duration was associated with frequency and entropy measurements; and to examine temporal relationships among consecutive events and intervals. Because all recordings originated from the same location and probably involved the same local social group, the results are interpreted as a description of within-group vocal organisation at this particular site rather than as a population-level characterisation of the species.

## Materials and Methods

### *Study area*

The recordings were obtained near the village of Zornitsa, Burgas Province, southeastern Bulgaria (Figure 1). The study site represents a rural landscape in which residential areas occur in close proximity to open and agricultural habitats used by golden jackals. All recordings were made from the same fixed location, using the same recorder position and approximately the same recording distance, during 18 evenings in October 2025 (autumn), approximately between 20:00 and 23:00h local time. The site was surveyed on 18 evenings, although golden jackal howling was not detected during every sampling session. Vocal activity was recorded intermittently on 11 evenings, from which eight sequences containing clearly identifiable spontaneous howling were selected for analysis. This standardised recording arrangement reduced variation associated with microphone placement among recording sessions.

**Figure 1. Location of the study site near Zornitsa village, Burgas Province, southeastern Bulgaria.** The map was prepared by the authors using QGIS v4.0.3. The study site was located at 42.384875° N, 26.929216° E. Basemap and administrative boundary data © OpenStreetMap contributors, available under the Open Database License.

### *Acoustic recordings*

The quantitative dataset comprised eight stereo audio recordings containing clearly detectable golden jackal (*Canis aureus*) vocal activity. Each recording was treated as a separate vocal sequence. The recordings were obtained during the evening using a Zoom H1 digital audio recorder and represented portions of naturally occurring vocal activity. The recordings were stored as mp3 files with a sampling rate of 44.1 kHz and a bit depth of 16 bit. No playback stimuli were used, and the animals were not approached or captured. The beginning and end of an analysed sequence corresponded to the period during which jackal vocalizations were clearly detectable at the fixed recording point.

No simultaneous visual observations were available. Consequently, the number, sex, age and identity of the vocalizing animals could not be determined. No attempt was made to estimate the total number of callers from the number of visible harmonic components in the spectrogram. Because all recordings originated from the same location, they probably represented repeated vocal activity of the same local social group; however, this could not be independently confirmed.

### *Signal identification*

The spectrograms showed clear differences between golden jackal howls and domestic dog barks (Figure 2a, b). Jackal howls were longer, harmonic sounds with clear frequency modulation, often produced in extended sequences. Dog barks were shorter, abrupt, broadband sounds, usually repeated in pulses and with less distinct frequency modulation. These differences were used to identify jackal vocalizations and exclude dog barks from the analysis. Wind, vehicles, human activity, and other background sounds were excluded because they lacked a coherent harmonic structure or a consistent vocal contour. Only clearly identifiable jackal vocalizations were retained. Additional recordings of domestic dogs were inspected qualitatively to assist differentiation between jackal howling and common dog vocalizations in the rural soundscape. These reference recordings were not included in any quantitative analysis.

Background sounds occurring between two identifiable jackal vocal events did not automatically invalidate the temporal interval. Therefore, the intervals analysed in this study represent the elapsed time between consecutive jackal events and should not necessarily be interpreted as completely silent pauses.

**Figure 2. Spectrogram of golden jackal (a) and domestic dog (b) vocalizations. Reproduced from Hristova (2026) under the Creative Commons Attribution 4.0 International License (CC BY 4.0).**

### *Spectrographic analysis*

Acoustic analysis was performed in Raven Pro software (Cornell Lab of Ornithology, Ithaca, NY, USA, Charif et al. 2010). Spectrograms were generated using a 1024-point fast Fourier transform, a Hann window and 50% temporal overlap between successive analysis frames.

All quantitative selections were analysed within a standardised frequency range of 150-5000 Hz. The same frequency boundaries were used for all recordings to ensure comparability among vocal events. Amplitude-based measurements were not interpreted because the distance and orientation of the callers could not be measured independently.

### *Definition of vocal events and inter-event intervals*

A vocal event, hereafter termed EVENT, was defined as a clearly distinguishable jackal acoustic element visible in the spectrogram and separated from the following event by a measurable temporal interval. Event boundaries were placed at the visually identifiable onset and offset of the acoustic signal.

An inter-event interval, hereafter termed IEI, was defined as the elapsed time between the end of one EVENT and the onset of the next identifiable EVENT within the same vocal sequence. IEIs therefore represented temporal separation between consecutive jackal vocalizations, irrespective of whether unrelated background sounds were present.

The final dataset contained 65 EVENTs and 57 IEIs distributed among the eight vocal sequences. Each sequence contained exactly one fewer IEI than EVENT, confirming that all intervals could be assigned to a preceding and a following vocal event. Overlapping or chorus-like harmonic components were noted descriptively during spectrogram inspection but were not used to estimate caller number or as a separate quantitative variable in the present statistical analysis.

### *Acoustic measurements*

The following measurements were extracted for each EVENT:

1. event duration, calculated as the difference between event offset and onset;
2. frequency 5%, representing the frequency below which 5% of the selection energy occurred;
3. centre frequency, representing the frequency dividing the selection energy into two equal portions;
4. frequency 95%, representing the frequency below which 95% of the selection energy occurred;
5. 90% bandwidth, calculated from the frequency 5% and frequency 95% limits;
6. peak frequency, representing the frequency with the highest measured energy;
7. aggregate entropy;
8. average entropy.

Spectral and entropy measurements were extracted only from EVENT selections. IEIs were analysed as temporal measurements.

### *Statistical analysis*

Individual vocal events (EVENTs) and inter-event intervals (IEIs) were used as the main units of analysis. The eight recordings were not considered independent biological replicates because all recordings were obtained from the same fixed location and probably represented repeated vocal activity of the same local social group. Therefore, recording identity was used as a blocking factor in additional permutation analyses in order to account for the grouping of observations within each vocal sequence.

The distribution of each variable was tested using the Shapiro-Wilk test. Because most temporal and acoustic variables were not normally distributed, descriptive statistics are presented both as mean ± standard deviation and as median with interquartile range, together with minimum and maximum values.

The durations of EVENTs and IEIs were compared using a two-sided Mann-Whitney U test. Cliff's delta was calculated to estimate the size of the difference between the two groups. In addition, the probability that a randomly selected EVENT was longer than a randomly selected IEI was derived from the Mann-Whitney statistic. A 95% confidence interval for the difference between the median EVENT duration and the median IEI duration was calculated using 100,000 bootstrap resamples.

To check whether the EVENT-IEI difference was robust to the structure of the dataset, a within-sequence permutation analysis was also performed. In this analysis, EVENT and IEI labels were randomly reassigned only within the same recording, while preserving the original number of EVENTs and IEIs in each vocal sequence.

Spearman rank correlations were used to test whether EVENT duration was associated with seven acoustic measurements: frequency 5%, centre frequency, frequency 95%, 90% bandwidth, peak frequency, aggregate entropy and average entropy. Because several correlations were tested, Benjamini-Hochberg false-discovery-rate correction was applied to reduce the risk of false-positive results.

***Temporal organisation was assessed using six sequential relationships:***

1. duration of an EVENT and duration of the following IEI;
2. duration of an IEI and duration of the following EVENT;
3. durations of consecutive EVENTs;
4. centre frequencies of consecutive EVENTs;
5. peak frequencies of consecutive EVENTs;
6. average entropy values of consecutive EVENTs.

For each sequential relationship, a Spearman correlation coefficient was calculated. Statistical significance was evaluated using 30,000 permutations in which the second variable was shuffled only within its original vocal sequence. This procedure preserved sequence membership and reduced the influence of systematic differences among recordings. Benjamini-Hochberg correction was applied across the six sequential tests.

Statistical significance was accepted at $p < 0.05$. For sets of multiple comparisons, an FDR-adjusted q value below 0.05 was considered statistically significant.

Statistical analyses were performed using SPSS v19 and Python. SPSS was used for descriptive statistics, normality testing, Mann-Whitney U tests and Spearman correlations. Python was used for effect-size calculation, bootstrap confidence intervals, within-sequence permutation analyses and false discovery rate correction.

**Results**

Descriptive statistics for temporal and acoustic measurements are presented in Table 1. EVENT duration ranged from 0.53 to 6.97 s, with a mean duration of 2.00 ± 1.22 s and a median duration of 1.76 s (IQR: 1.26-2.21 s). IEI duration ranged from 0.10 to 8.71 s, with a mean duration of 1.35 ± 1.60 s and a median duration of 0.78 s (IQR: 0.41-1.54 s).

**Table 1. Descriptive statistics of acoustic measurements.**

Most EVENTs were relatively short. A total of 48 out of 65 EVENTs (73.8%) had durations between 1 and 3 s, whereas 9 EVENTs (13.8%) were shorter than 1 s. Only 8 EVENTs (12.3%) were longer than 3 s. IEIs were generally shorter than EVENTs: 36 out of 57 IEIs (63.2%) were shorter than 1 s, including 21 IEIs (36.8%) shorter than 0.5 s. This distribution indicates that the vocal sequences were characterised by compact temporal organisation, with short intervals separating consecutive acoustic events.

The acoustic-energy distribution of EVENTs showed that the main energy of the calls was concentrated predominantly below 2 kHz. The median frequency 5% was 656.3 Hz (IQR: 281.3-689.1 Hz), the median centre frequency was 843.8 Hz (IQR: 775.2-861.3 Hz), and the median frequency 95% was 1636.5 Hz (IQR: 1378.1-2325.6 Hz). The median 90% bandwidth was 1119.7 Hz (IQR: 775.2-1781.3 Hz), while the median peak frequency was 775.2 Hz (IQR: 602.9-861.3 Hz). Aggregate entropy had a median value of 3.33 bits (IQR: 2.63-3.67 bits), and average entropy had a median value of 2.69 bits (IQR: 2.54-3.02 bits).

**Figure 3. Percentage distribution of vocal-event and inter-event interval durations among five mutually exclusive duration categories.** Percentages were calculated separately for the 65 vocal events (EVENTs) and 57 inter-event intervals (IEIs). Numerical labels above the bars indicate the percentage of observations withing each category.

Most vocal events lasted between 1 and 3 s, whereas most inter-event intervals were significantly shorter than 1 s, indicating compact temporal organization of the vocal sequences (Figure 2). The median EVENT duration was 1.76 s, whereas the median IEI duration was 0.78 s. The median difference between EVENT and IEI duration was 0.98 s, with a bootstrap 95% confidence interval of 0.60-1.34 s (Figure 3).

The two-sided Mann-Whitney U test confirmed a statistically significant difference between EVENT and IEI durations ($U = 2780.5$, $p < 0.001$). The effect size was moderate to large, as indicated by Cliff's delta ($\delta = 0.501$). The probability that a randomly selected EVENT was longer than a randomly selected IEI was 75.0%. The result was also supported by the within-sequence permutation analysis, which remained highly significant ($p < 0.00001$). These findings show that individual vocal events were consistently longer than the intervals separating them.

**Figure 4. Distribution of vocal-event and inter-event interval durations.** Boxes represent the interquartile range, and the horizontal orange lines indicate the medians. Whiskers extend to the most extreme observations within 1.5 times the interquartile range. Green triangles indicate arithmetic means, while open circles represent observations beyond the whiskers; these observations were retained in the statistical analysis. EVENTs ($n = 65$) were longer than IEIs ($n = 57$; Mann–Whitney $U = 2780.5$, $p < 0.001$, Cliff's $\delta = 0.501$).

Spearman rank correlations were used to test whether EVENT duration was associated with the measured acoustic parameters. No significant associations were found between EVENT duration and frequency 5%, centre frequency, frequency 95%, 90% bandwidth, peak frequency, aggregate entropy or average entropy after false-discovery-rate correction. All blocked FDR-adjusted q values were ≥ 0.963. Thus, longer vocal events were not systematically associated with higher or lower frequency values, broader bandwidth or increased spectral entropy. In the present dataset, temporal duration and spectral-energy structure appeared to represent largely independent dimensions of variation.

Sequential analyses revealed significant temporal relationships among neighbouring components of the vocal sequences (Table 2). The duration of a vocal event was positively associated with the duration of the following IEI (Spearman's ρ = 0.314, permutation p = 0.0040, FDR q = 0.0238). This indicates that longer vocal events tended to be followed by longer intervals. A second significant positive association was found between IEI duration and the duration of the following EVENT (ρ = 0.288, permutation p = 0.0153, FDR q = 0.0306). Therefore, longer intervals tended to precede longer subsequent vocal events.

**Table 2. Sequential organization**

The strongest temporal relationship was observed between the durations of consecutive EVENTs. Adjacent vocal events showed a strong positive association in duration (ρ = 0.702, permutation p = 0.0104, FDR q = 0.0306), indicating that longer events tended to occur near other longer events, while shorter events tended to be followed by shorter ones.

No significant sequential relationships were found for centre frequency, peak frequency or average entropy of consecutive EVENTs after FDR correction. Although consecutive EVENT centre frequencies and average entropy values showed positive raw correlations, these relationships did not remain significant after within-sequence permutation and correction for multiple comparisons.

Overall, the sequential results indicate that the recorded howling was temporally organised rather than composed of independent acoustic emissions. The strongest evidence of organisation was observed in the duration of adjacent vocal events and in the coupling between vocal-event duration and neighbouring inter-event intervals.

## Discussion

Animal communication is determined not only by the spectral structure of individual calls but also by their duration, repetition, ordering, and the intervals separating them (Kershenbaum et al. 2016). The present results show that these temporal components are not independent: the duration of an event was related to the following interval, interval duration was related to the subsequent event, and adjacent events displayed similar durations. These relationships reveal a previously insufficiently described temporal layer of golden jackal howling. Identifying such regularities is an essential step towards understanding the overall vocal behavior of golden jackals, and particularly how vocal sequences are organized and how information may be encoded in them. And as Konrad Lorenz once said, "when we understand the signal code of a species, then we will have learned its vocabulary" (Lorenz 1952).

The present study provides an event-level description of the temporal and acoustic organisation of golden jackal howling recorded near a rural settlement in southeastern Bulgaria. Across eight vocal sequences, 65 individual vocal events and 57 inter-event intervals were identified. The results demonstrate that the recorded vocal activity was not composed of isolated, randomly

distributed calls. Instead, the events were embedded in compact and statistically structured temporal sequences. The recordings probably originated from the same local social group and therefore describe within-group variability at one site rather than variation among independent groups or populations. Individual vocal events had a median duration of 1.76 s, whereas inter-event intervals had a median duration of 0.78 s. Vocal events were significantly longer than the intervals separating them, with a moderate to large effect size (Mann-Whitney $U = 2780.5$, $p < 0.001$, Cliff's $\delta = 0.501$). In addition, 63.2% of all inter-event intervals were shorter than 1 s. These findings indicate a relatively dense acoustic organisation in which short interruptions separate repeatedly emitted vocal elements. Such temporal compactness is consistent with the general complexity of long-distance vocal sequences described in social canids, in which howls may occur as repeated or partly coordinated units rather than as completely independent sounds (Passilongo et al. 2017, 2010).

A particularly important finding was the presence of significant temporal relationships between adjacent components of the vocal sequences. Longer vocal events tended to be followed by longer inter-event intervals, and longer intervals tended to precede longer subsequent events. The durations of consecutive vocal events were also strongly and positively associated. Together, these relationships indicate temporal persistence within the sequences: relatively long events tended to occur near other long events and to be separated by relatively long intervals, whereas shorter events tended to form more rapidly repeated sequences. This pattern may reflect sequence-level pacing, shared motivational state, respiratory constraints or coordinated vocal production. However, the present recordings do not allow these alternative explanations to be distinguished. Because individual callers were not identified, the observed relationships cannot be interpreted as evidence of turn-taking between particular animals. Similarly, they cannot determine whether successive events were produced by one individual or by several members of the group. The results should therefore be described as evidence of structured acoustic timing rather than direct evidence of individual behavioural coordination.

The strong similarity between the durations of adjacent events suggests that the temporal properties of the vocal activity remained locally stable over short parts of a sequence. Comparable organisation has been documented in other social canids, in which howl structure can vary according to individual, social group and behavioural context (Root-Gutteridge et al. 2014, Zaccaroni et al. 2012, Palacios et al. 2007, Tooze et al. 1990). Nevertheless, the current analysis concerns the duration and order of acoustic units and does not demonstrate an individual or group-specific vocal signature. Confirming such signatures would require repeated recordings from visually or genetically identified animals.

No statistically significant relationships were found between event duration and frequency 5%, centre frequency, frequency 95%, 90% bandwidth, peak frequency, aggregate entropy or average entropy after correction for multiple comparisons. Thus, longer events were not consistently higher- or lower-frequency, more broadband or more spectrally disordered than shorter events. Duration and spectral-energy structure therefore appear to represent partly independent dimensions of variation in this dataset. The absence of duration-frequency relationships should not be interpreted as evidence that spectral properties lack communicative significance. Studies of wolves have demonstrated that frequency modulation, fundamental-frequency characteristics and acoustic-energy distribution may encode information about caller identity, group membership or chorus composition (Palacios et al. 2016, Root-Gutteridge et al. 2014, Zaccaroni et al. 2012, Tooze et al. 1990). Rather, the current results show that this information, if present in golden jackal howling, was not expressed as a simple linear or monotonic relationship with event duration. Further analyses using identified callers, fundamental-frequency contours and controlled recording distances would be required to examine signal identity and social information.

The recordings were repeatedly obtained from the same location and probably involved the same local family or social group. Golden jackal groups may remain relatively stable and may include a breeding pair together with offspring from one or more cohorts (Custers et al. 2024, Macdonald 1979). The observed variation among sequences may therefore reflect changes in the momentary social, spatial or motivational context of one group rather than differences among unrelated populations. This interpretation is consistent with the objective of the study, which was to characterise the vocal behaviour of a local group at a specific rural site.

The occurrence of structured vocal activity near a human settlement also supports the usefulness of passive acoustic monitoring in human-modified landscapes. Previous studies have demonstrated that golden jackal howls can be detected and analysed using autonomous or fixed recording systems (Smith et al. 2025, Graf and Hatlauf 2021, Comazzi et al. 2016). Passive recordings may therefore provide valuable behavioural information even when direct observation is not possible. At the same time, the acoustic composition of a recording depends on the distance and orientation of the callers, propagation conditions, vegetation, topography and background noise. Howls may become weak or disappear from the recording while the behavioural episode continues outside the effective detection range.

The present findings, together with previous successful autumn acoustic surveys in Romania and earlier observations of increased spontaneous howling between September and December in Bulgaria, support autumn, including October, as a suitable period for acoustic monitoring of golden jackals (Acosta-Pankov et al. 2018, Banea et al. 2012). Autumn passive monitoring may be particularly appropriate for recording and analyzing spontaneously produced vocal sequences. However, because the present study did not compare seasons, autumn cannot be identified as the period of maximum detectability. For programmes using playback to determine presence or territorial-group density, summer surveys, particularly between June and August, may provide higher response rates, whereas spring can be used as a complementary period.

The fixed recording position reduced variation associated with recorder placement, but several limitations remain. The number, identity, age and sex of the vocalizing animals were unknown, and there was no simultaneous visual confirmation. Consequently, the number of distinguishable acoustic components cannot be equated with the number of animals present. Spectrographic studies of wolf choruses have shown that overlapping components may assist in estimating a minimum chorus size, but such estimates depend strongly on recording quality and should not be interpreted as total group size (Passilongo et al. 2015). The present study therefore deliberately avoided estimating the number of participating jackals.

Despite these limitations, the consistency of the event-level results indicates that short field recordings can contain biologically informative temporal structure. The significant relationships between consecutive events and intervals show that the local group's howling was organised into temporally coherent sequences. Future work should combine longer-term passive monitoring with microphone arrays, camera traps, thermal imaging or GPS data. Such integration would permit acoustic sequences to be linked to caller number, individual identity, group movement and behavioural context. Sampling additional locations and seasons would also be necessary to determine whether the temporal patterns identified here are characteristic of golden jackals more broadly or are specific to this local group.

## Conclusion

In conclusion, golden jackal howling recorded near the rural settlement was characterised by vocal events that were longer than the intervals separating them, a predominance of short inter-event intervals and significant temporal coupling among consecutive acoustic units. Event duration was not systematically related to the measured spectral or entropy parameters. These

findings provide evidence that the evening vocal activity of this local group was temporally structured and demonstrate the value of event-level passive acoustic analysis for studying free-ranging golden jackals in human-modified environments. Our October recordings demonstrate that autumn passive acoustic monitoring is suitable for studying spontaneous golden jackal howling.

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**Table 1. Descriptive statistics of acoustic measurements.**

| Variable | n | Mean ± SD | Median (IQR) | Min-max |
|---|---|---|---|---|
| EVENT duration, s | 65 | 2.00 ± 1.22 | 1.76 (1.26-2.21) | 0.53-6.97 |
| IEI duration, s | 57 | 1.35 ± 1.60 | 0.78 (0.41-1.54) | 0.10-8.71 |
| Frequency 5%, Hz | 65 | 521.8 ± 224.8 | 656.3 (281.3-689.1) | 172.3-843.8 |
| Center frequency, Hz | 65 | 822.2 ± 281.3 | 843.8 (775.2-861.3) | 187.5-1593.8 |
| Frequency 95%, Hz | 65 | 1811.7 ± 771.5 | 1636.5 (1378.1-2325.6) | 281.3-3562.5 |
| 90% bandwidth, Hz | 65 | 1289.8 ± 748.7 | 1119.7 (775.2-1781.3) | 93.8-2906.3 |
| Peak frequency, Hz | 65 | 803.1 ± 488.7 | 775.2 (602.9-861.3) | 172.3-3000.0 |
| Aggregate entropy, bits | 65 | 3.12 ± 0.80 | 3.33 (2.63-3.67) | 0.67-4.49 |
| Average entropy, bits | 65 | 2.71 ± 0.47 | 2.69 (2.54-3.02) | 0.98-3.56 |

**Table 2. Sequential organization**

| Sequential relationship | Pairs, n | Spearman's ρ | Permutation p | FDR q |
|---|---|---|---|---|
| Preceding EVENT duration → following IEI | 57 | **0.314** | **0.0040** | **0.0238** |
| IEI duration → following EVENT duration | 57 | **0.288** | **0.0153** | **0.0306** |
| Consecutive EVENT durations | 57 | **0.702** | **0.0104** | **0.0306** |
| Consecutive EVENT center frequencies | 57 | 0.473 | 0.1401 | 0.1681 |
| Consecutive EVENT peak frequencies | 57 | 0.257 | 0.4368 | 0.4368 |
| Consecutive EVENT average entropy | 57 | 0.438 | 0.0361 | 0.0541 |

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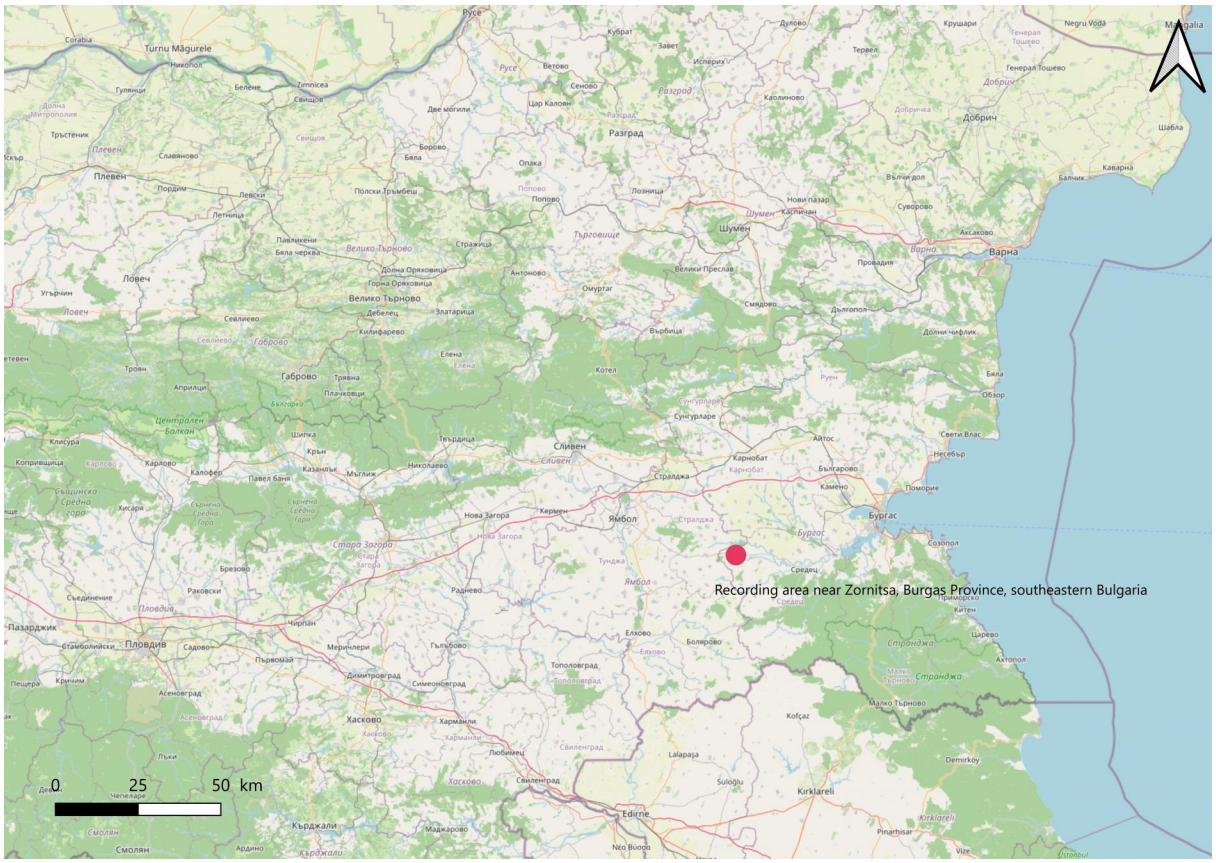
Recording area near Zornitsa, Burgas Province, southeastern Bulgaria
0
25
50 km

Figure 1

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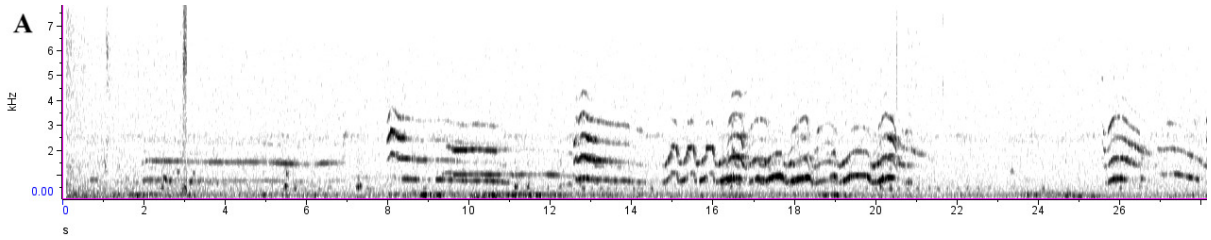

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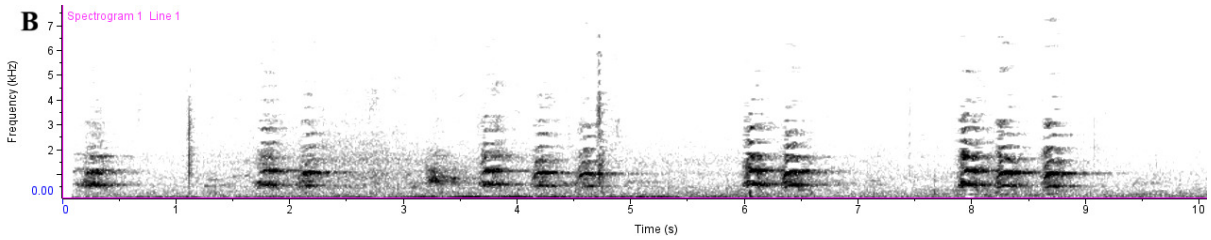
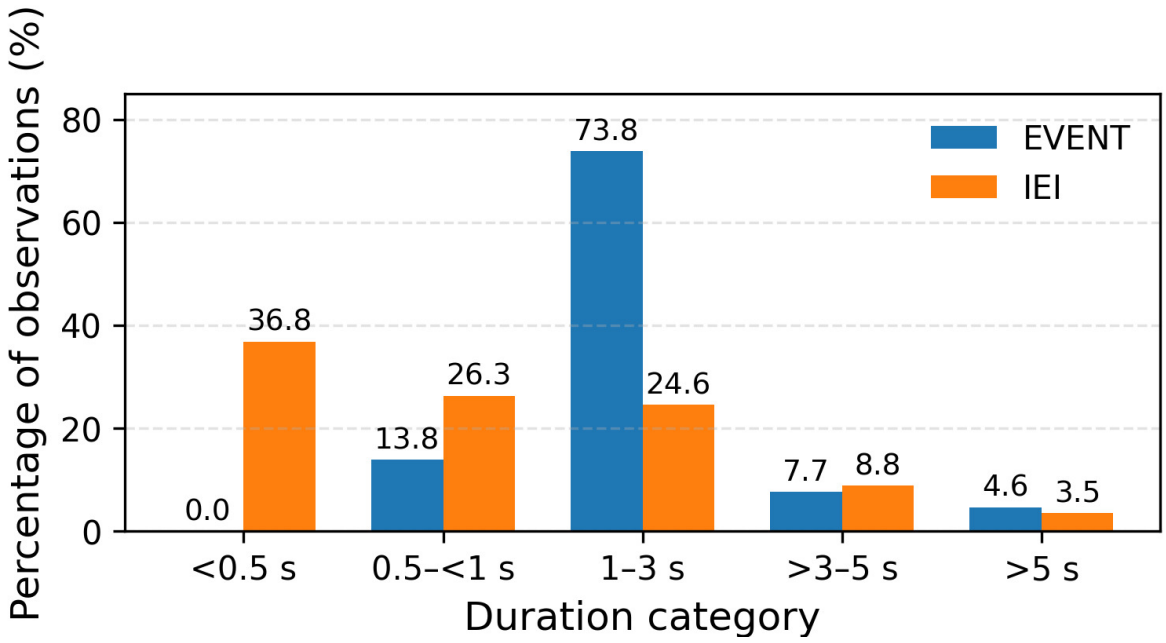
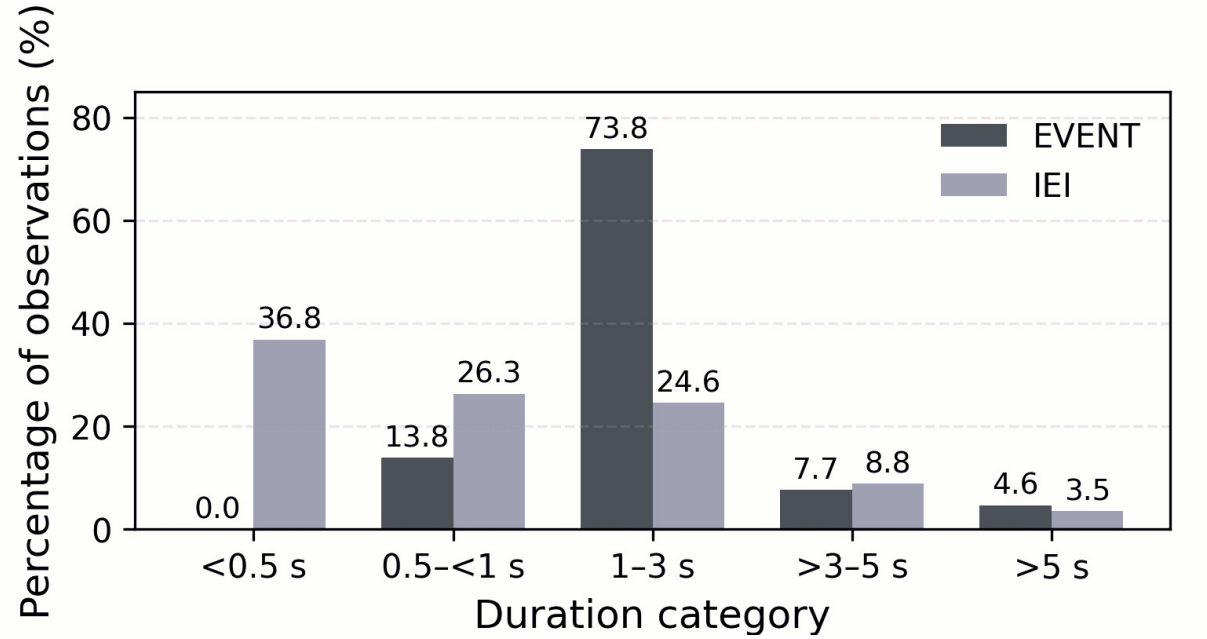
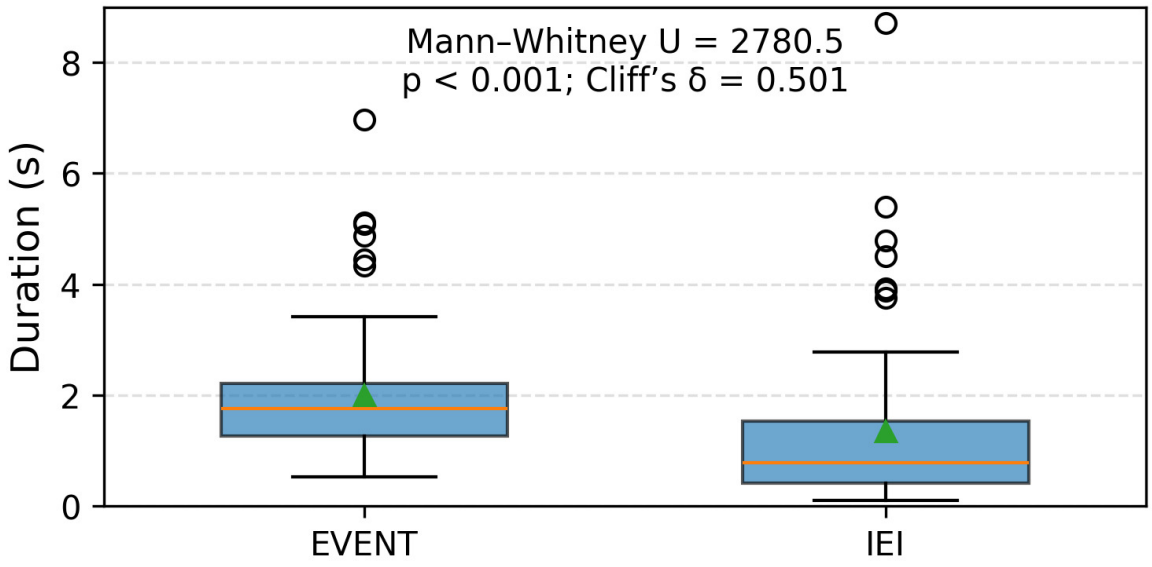



Percentage of observations (%)
80
60
40
20
0
EVENT
IEI
0.0
36.8
13.8
26.3
73.8
24.6
7.7
8.8
4.6
3.5
<0.5 s
0.5–<1 s
1–3 s
>3–5 s
>5 s
Duration category


Percentage of observations (%)
80
60
40
20
0
EVENT
IEI
0.0
36.8
13.8
26.3
73.8
24.6
7.7
8.8
4.6
3.5
<0.5 s
0.5–<1 s
1–3 s
>3–5 s
>5 s
Duration category


Mann–Whitney U = 2780.5
p < 0.001; Cliff's δ = 0.501
Duration (s)
0
2
4
6
8
EVENT
IEI

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