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1 **Solo: an open source, customisable and inexpensive audio recorder for bioacoustic**
2 **research**

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9

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18 (1) **Solo website** <https://solo-system.github.io/>

19 (2) **Video tutorial** <https://youtu.be/2Fq05JIEKjw>

20 **Summary**

- 21 1. Audio recorders are widely used in terrestrial and marine ecology, and are essential for
22 studying many cryptic or elusive taxa. Although several commercial systems are
23 available they are often expensive and are rarely user-serviceable or easily customised.
- 24 2. Here, we present the Solo audio recorder. Units are constructed from the Raspberry Pi
25 single board computer and run easy-to-install and freely available software. We provide
26 an example configuration costing £167 (£83 excluding suggested memory card and
27 battery), which records audible sound continuously for approximately 40 days. We also
28 provide a video tutorial showing hardware assembly and documentation is available via
29 a supporting website.
- 30 3. The Solo recorder has been extensively field tested in temperate and tropical regions,
31 with over 50,000 hours of audio collected to date. This highly customisable and
32 inexpensive system could greatly increase the scale and ease of conducting bioacoustic
33 studies.

34 **Introduction**

35 Bioacoustics has improved our understanding of evolution, taxonomy, wildlife conservation
36 and animal physiology (Blumstein et al. 2011). Many birds (*Aves*) and invertebrates produce
37 territorial song, bats (*Chiroptera: Microchiroptera*) use ultrasound to detect prey, and
38 elephants *Loxodonta* sp. use infrasound to communicate. Calls and songs are often unique
39 to a species, and in many instances convey the biological, behavioural and ecological
40 characteristics of the source. Acoustic recordings can therefore reveal a wealth of
41 information about individuals, populations and the environment.

42

43 Outside the laboratory, ecological sounds are typically recorded using remotely operated or
44 handheld devices (Efford et al. 2009; Bardeli et al. 2010; Blumstein et al. 2011; Marques et
45 al. 2013; Cerquiera & Aide 2016). Automated systems that record continuously or in
46 response to acoustic triggers have become increasingly popular, and can be deployed in
47 isolation or complex spatial arrays (e.g. Mennill et al. 2012). These are suitable for a variety
48 of ecological applications ranging from simple species presence/absence surveys to tracking
49 acoustically active animals in three-dimensional space, and identifying individuals from their
50 unique vocalisations. Such systems are indispensable for studying cryptic taxa such as bats,
51 and for detecting elusive, nocturnal or rare species. However, although deploying small
52 numbers of commercially available recording units (e.g. Wildlife Acoustics' Song Meter) can
53 be affordable (Mennill et al. 2012), deploying large numbers (e.g. for landscape-scale
54 studies) can be costly. Relatively inexpensive systems based on tablet computers have
55 become available more recently (Aide et al. 2013; Cerquiera & Aide 2016). However, the
56 core components of these systems are rarely user-serviceable and they often contain

57 unnecessary hardware and software that becomes redundant when used for bioacoustic
58 research.

59

60 Inexpensive single board computers have become widely available in the past decade. For
61 example, the Raspberry Pi single board computer (c. £20 at time of writing), which was
62 originally developed as an educational tool, has been adapted for a broad variety of
63 applications. These and similar devices, such as the BeagleBone Black development board
64 consume minimal power and use high-specification hardware relative to their small size and
65 low cost. Furthermore, they are operated using freely distributed and readily available open
66 source, Unix-based operating systems, and can be powered by any DC battery, such as USB
67 charging devices or vehicle batteries. These features make single board computers like the
68 Raspberry Pi highly customisable, and they have many potential applications in ecology.

69

70 Here, we introduce the Solo audio recorder. The system records audible sound up to 22.05
71 kHz for long periods (> one month) without user intervention, and can also record audio up
72 to a Nyquist frequency of 96 kHz (i.e. sampling rate of 192 kHz). The Solo is straightforward
73 to build and operate, and is constructed from inexpensive hardware and freely available
74 software. Solos have proven to be robust during extensive field testing in temperate and
75 tropical environments, and users can customise the software or hardware configuration to
76 suit research needs.

77

78

79 **System overview**

80 Solos (Figure 1) are operated using custom-written software and the current version is
81 available online from <https://solo-system.github.io/>. The core system comprises a Raspberry
82 Pi single board computer (Farnell element14, Leeds, UK), PiFace clock module (OpenLX SP
83 Ltd, London, UK) and Cirrus Logic audio card (Cirrus Logic, Austin, Texas, USA; CLAC).
84 Although other suitable single-board computers are available, we chose the Raspberry Pi as
85 the foundation of the Solo, since it was the first single-board computer to be generally
86 available, it was rapidly successful and the software is now widely supported and debugged.
87 It also supports the CLAC high definition audio card, which has a sampling rate of up to 192
88 kHz.

89

90 The Solo is compatible with a wide range of external microphones, and accepts microSD
91 cards and any 5 V power supply (Box 1). Using the default software configuration, the Solo
92 records audio continuously at a sampling rate of 16 kHz (8 kHz Nyquist) in .wav format
93 (saved as individual ten minute, time stamped sections) until the power supply is removed
94 or the memory card reaches storage capacity. However, the audio file section length, time
95 zone, sampling rate and microphone gain can be configured to suit research requirements.
96 Source code is also available via the supporting website for advanced users who wish to
97 customise the software.

98 **Field testing**

99 ***Audible sound***

100 Approximately 52,381 hours of audible sound have been recorded to date by 40 Solos using
101 a variety of hardware and software configurations. Five systems ($n = 600$ hours recorded)
102 were deployed in the Ebo forest, southwest Cameroon during the wet season in 2015,
103 where annual rainfall is approximately 3,500 mm. A further ten systems ($n = 10,383$ hours
104 recorded) were deployed between February and June 2015 in Central Scotland and Central
105 England as part of a pilot study of long-eared owl *Asio otus* and tawny owl *Strix aluco*
106 ecology in association with the British Trust for Ornithology. Finally, approximately 41,398
107 hours of audio ($n = 35$ systems) were recorded in 2015 and 2016 in Central Scotland and
108 Central England as part of the Woodland Creation and Ecological Networks (WrEN) project
109 (Watts et al. 2016). Four spectrograms of bird song recorded using the example
110 configuration presented here are shown in Figure 2.

111

112 ***Ultrasound***

113 The ultrasound capabilities of the Solo have not been tested extensively, nonetheless there
114 is considerable scope for development given the maximum sampling rate of 192 kHz. During
115 a small scale field test in Central Scotland ($n = 240$ hours from five systems), foraging calls of
116 soprano pipistrelle *Pipistrellus pygmaeus* were recorded (Figure 3). This was achieved using
117 the example hardware configuration given below and setting the sampling rate to 192 kHz.
118 The Solo was positioned on the ground beneath a known roost, and bats emerged and
119 foraged approximately 3 - 4 m above the microphone.

120 There is considerable scope for developing the ultrasound capabilities of the Solo. We
121 recommend that anyone interested in recording ultrasound should experiment with
122 alternative microphones, such as the Knowles FG series (Knowles, Itasca, Illinois, USA).

123

124 **Example hardware configuration**

125 The example hardware configuration (Table 2) described here was designed to record
126 breeding woodland birds in temperate broadleaved woodland as part of the WrEN project,
127 and it was found to be the most cost-effective configuration relative to battery life and
128 audio quality. Using the default software settings, this configuration will record at a
129 sampling rate of 16 kHz continuously (i.e. 24/7) for approximately 40 days during
130 deployment (mean = 39.8, SE = 0.9 days, $n = 24$ systems with available data). See the
131 supporting website <https://solo-system.github.io/> and video tutorial
132 <https://youtu.be/2Fq05JIEKjw> for a full description of how to build, operate and customise a
133 Solo recorder.

134 ***Data retrieval***

135 Using the default configuration, audio is stored in a folder-per-day hierarchy as 10 minute
136 sections. The data are stored on a dedicated partition on the microSD card and are accessed
137 by using a computer and SD card reader. Free software may be required by non-Linux users
138 to access the partition (see supporting website).

139 **Discussion**

140 The Solo is a reliable, inexpensive, highly customisable audio recorder that can operate in
141 remote locations for long time periods without user intervention. Example applications
142 include landscape-scale studies (e.g. Watts et al. 2016) where dozens of systems might be
143 required to achieve sufficient sample sizes, or deployment in situations where there is a

144 high risk of the device being destroyed (e.g. by vandalism). Citizen science data are also
145 increasingly used in ecological and conservation research (e.g. Newson et al. 2015; Kobori et
146 al. 2016), and the Solo could increase participation in large-scale bioacoustic studies where
147 the expense of commercial systems potentially limits participation.

148

149 Another advantage of the Solo over several existing systems is that it is predominantly built
150 from open source hardware and software, and it can accept a wide variety of off-the-shelf
151 microphones and power supplies. These features not only future-proof the system, but also
152 make it user-serviceable, thus encouraging modification and development by the end user
153 to suit specific research needs. Although commercial systems are likely to remain popular
154 with those who require the additional benefits of warranties, customer services and out-of-
155 the-box usability, the Solo recorder offers unprecedented flexibility at a fraction of the cost,
156 which itself is likely to reduce over time given price trends in technology.

157

158 ***Directions for future development***

159 At present, the Solo does not have a scheduling function, which would allow audio to be
160 recorded only during predetermined time periods rather than continuously. In some audio
161 recorders this can increase battery life. However, the Raspberry Pi does not have an
162 efficient low-power mode, and a scheduling function would not therefore reduce power
163 consumption significantly. Nonetheless, scheduling would improve storage capacity, which
164 is of particular concern when recording at high sampling rates. In particular, scheduling is
165 likely to be essential for recording taxa that are only active during short periods of the day
166 and emit ultrasound, such as many bats and invertebrates. Furthermore, advanced
167 scheduling could be used to improve the scope of field studies. For example, sampling rates

168 could be changed according to prescheduled times, perhaps recording audible sound during
169 daylight and ultrasound at night.

170

171 Audio is currently recorded in raw uncompressed .wav format, which requires
172 approximately double the storage space of a compressed lossless format such as .flac, and
173 future versions of the Solo software image could offer users a range of audio format options
174 to address this. Furthermore, although the Solo can be operated for long time periods
175 unattended, the user must collect the data and refresh the battery periodically, which may
176 be difficult in some circumstances. Other systems are capable of wirelessly transmitting data
177 to a base station (e.g. Aide et al. 2013), which addresses this problem. These capabilities
178 could also be implemented in future Solo versions.

179

180 Finally, the processing power and potential functionality of the Raspberry Pi is underused by
181 the Solo system in its current form, and the Raspberry Pi has the capacity to support many
182 other features not discussed here. Examples include the addition of acoustic triggers that
183 only record sounds above a specified amplitude, on-board data processing (e.g. species
184 detection), a digital display, wireless communication in the field (e.g. with a smart phone or
185 tablet) and the addition of peripherals (e.g. temperature loggers).

186

187 **Conclusion**

188 The Solo is an open source, customisable and inexpensive system for collecting high
189 definition, long-term audio data. It has several advantages over comparable systems, and its
190 introduction here (1) makes high-quality equipment accessible to those with limited
191 resources, (2) improves the feasibility of conducting bioacoustic research across

192 representative spatiotemporal scales, and (3) has the potential to advance the field of
193 bioacoustics through the development of novel hardware and software configurations,
194 leading to improved data collection.

195

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205

206 **Author contribution statement**

207 JC developed the software and RW contributed to design. RW led field testing and writing of
208 the manuscript. Both authors contributed critically to drafts and gave final approval for
209 publication.

210

211 **Data accessibility**

212 This manuscript does not use any data.

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245

Box 1. Hardware options

Raspberry Pi (essential): The following Raspberry Pi models have been tested: A+, B+, 2B, 3B, Pi Zero (the last model requires soldering). The Raspberry Pi A+ was used during all field testing because it has the lowest power consumption.

Cirrus Logic audio card (essential): Provides a high-fidelity (up to 192 kHz sampling rate) interface between the Raspberry Pi and an external microphone. The CLAC also has an internal stereo microphone, but this is difficult to weatherproof and an external microphone is recommended for field deployment.

External microphone/s (optional): The CLAC supports an external microphone (mono or stereo pair) with a 3.5 mm jack input (converters are widely available, e.g. from XLR to 3.5 mm jack). 2 – 3V of plug-in-power can be supplied to the microphone via the CLAC if required.

PiFace clock module (optional): Used to store the date and time of recordings and is powered by a button cell battery (CR1220). It must be set up prior to deployment using a network connection (see <https://solo-system.github.io/>).

Power: Any 5 V power supply (micro-USB) providing a minimum of 700 mA is suitable, such as a USB travel charger or 12 V car battery with a 5 V converter and micro-USB adapter. A mains supply can also be used if available. Using a Raspberry Pi A+, the units consume approximately 0.35 W during operation.

Memory: The Raspberry Pi accepts a single microSD card of any size. The Solo software image requires approximately 1.5 GB of memory space and the remainder is used to store audio data. Table 1 shows estimated storage requirements for various sampling rate and memory card size combinations.

247 **Table 1.** Approximate storage capacity (hours in .wav format) of different microSD memory
248 card sizes and sampling rate combinations when recording on a single channel. These values
249 should be halved when recording in stereo.

| | 8 GB | 16 GB | 32 GB | 64 GB | 128 GB | 256 GB |
|-----------------|-------------|--------------|--------------|--------------|---------------|---------------|
| 8 kHz | 112 | 251 | 529 | 1085 | 2196 | 4418 |
| 16 kHz | 56 | 125 | 263 | 524 | 1098 | 2209 |
| 44.1 kHz | 20 | 45 | 96 | 196 | 398 | 801 |
| 192 kHz | 4 | 10 | 22 | 45 | 91 | 184 |

250

251

252 **Table 2.** Components used to build the example Solo hardware configuration, approximate
 253 cost and manufacturer details. Suggested websites for purchasing non-generic components
 254 are also given.

| Component | Cost (£) | Model | Manufacturer | Website |
|-------------------------------|-------------|--|--|---|
| Raspberry Pi | 15 | Model A+ (lowest power consumption available) | Farnell element14, Leeds, UK | http://uk.farnell.com |
| Cirrus Logic Audio Card | 24 | One model | Cirrus Logic, Austin, Texas, USA | http://uk.farnell.com |
| PiFace clock | 9 | Clock module with dedicated button-cell battery (CR1220) | OpenLX SP Ltd, London, UK | http://uk.farnell.com |
| 128 GB microSD memory card | 40 | SanDisk Ultra SDXC class 10 | SanDisk, Milpitas, California, USA | - |
| Car battery | 44 | 063XD: 12 V, 50 Ah | generic | - |
| Battery terminal clamp | 2 | 12 V car battery terminal clip | generic | - |
| 12 V to 5 V converter | 9 | DC-DC 12V To 5V converter module with USB adapter 15 W 3 A | generic | - |
| Microphone | 15 | Clippy EM172 model FC049 | Primo Microphones, Inc. Mckinney, Texas, USA | http://micbooster.com/ |
| Plastic electronics enclosure | 1 | Business card box | generic | |
| DRiBOX | 8 | FL-1859-200 | DRiBOX, Black River Falls, Wisconsin, USA | http://dri-box.com/ |
| Total cost | £167 | | | |

255

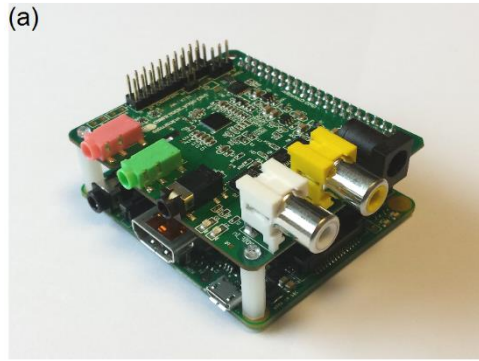
256 **Figure legends**

257 **Figure 1.** Illustrative examples of assembled Solo recorders; (a) Raspberry Pi A+ and CLAC,
258 (b) Raspberry Pi A+ and CLAC with attached EM172 microphone and USB travel charger as a
259 power supply, (c) example configuration (see text) deployed in a woodland (driBox lid
260 removed to show contents).

261 **Figure 2.** Spectrograms (Hanning window length = 256) of four bird songs recorded using
262 the example Solo configuration. The Solo was deployed in the middle of a small (c. 1 ha)
263 broadleaved woodland in Central Scotland. No post processing was performed.

264 **Figure 3.** Spectrogram (Hanning window length = 1024) showing foraging calls of a soprano
265 pipistrelle. No post processing was performed.

266

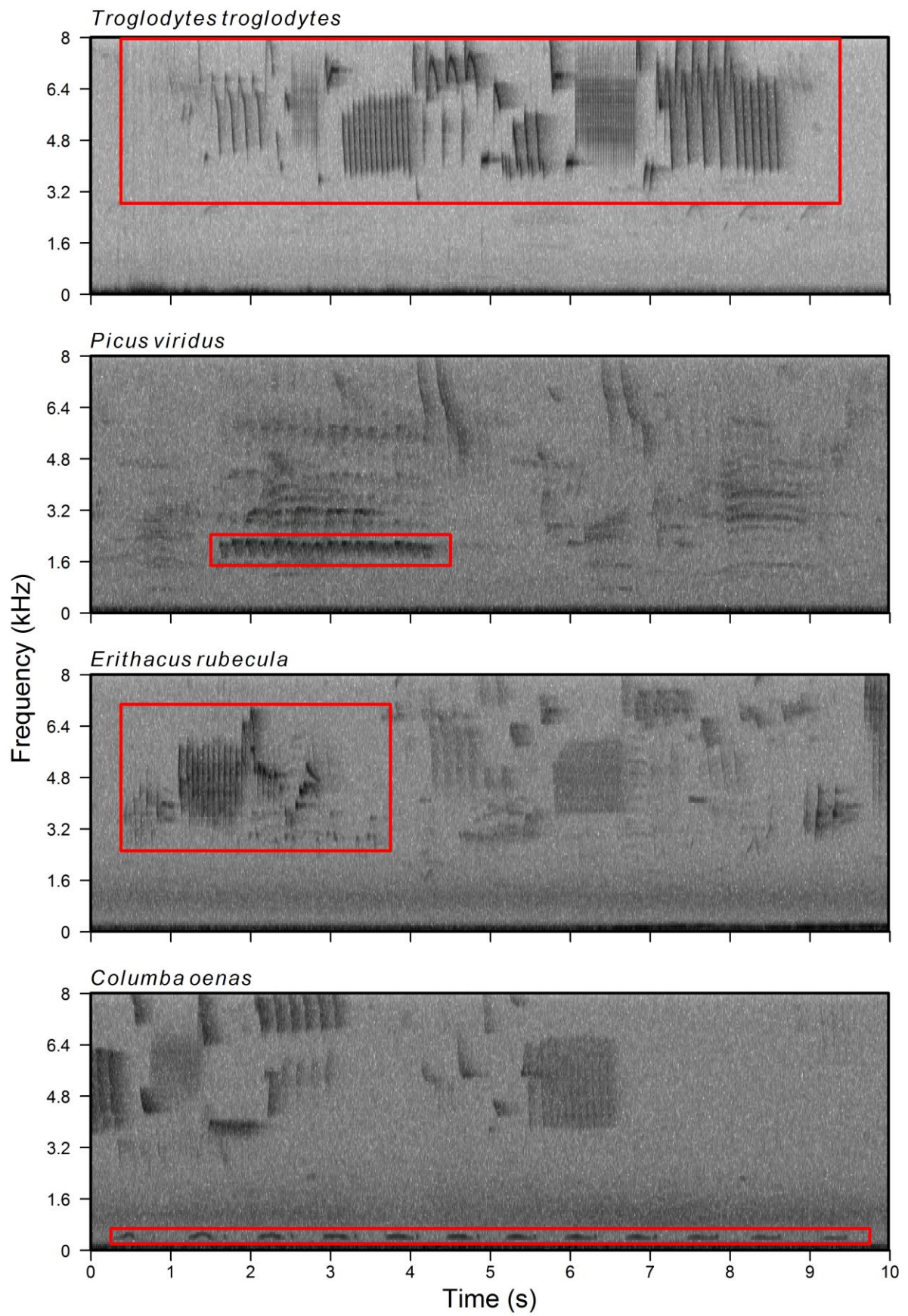


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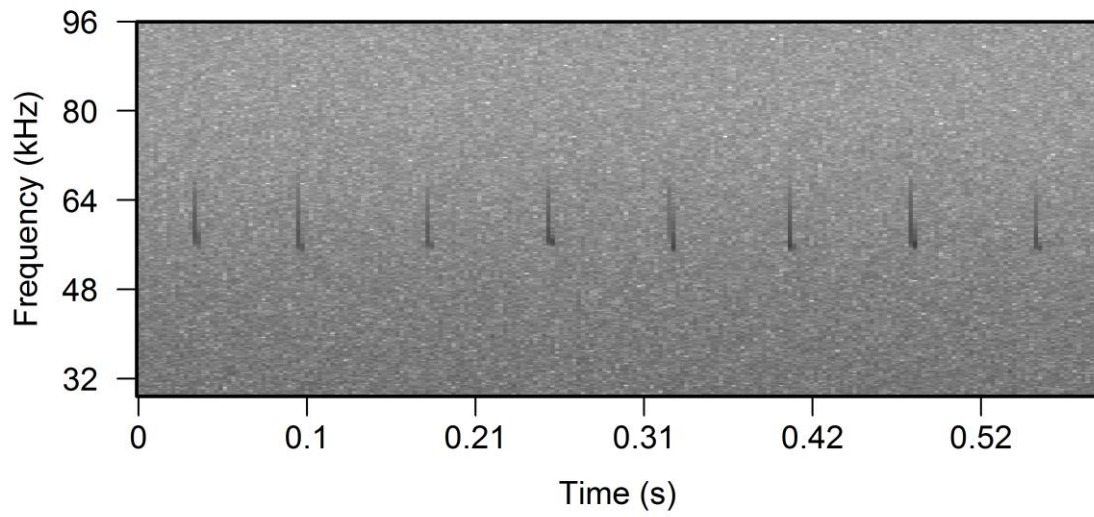
269

Figure 1



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 271
 272

Figure 2



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Figure 3