






# BatRack: An open-source multi-sensor device for wildlife research

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## Abstract

1. Bats represent a highly diverse group of mammals and are essential for ecosystem functioning. However, knowledge about their behaviour, ecology and conservation status is limited. Direct observation of marked individuals (commonly applied to birds) is not possible for bats due to their small size, rapid movement and nocturnal lifestyle, while neither popular observation methods such as camera traps nor conventional tracking technologies sufficiently capture the behaviour of individuals. The combination and networking of different sensors in a single system can overcome these limitations, but this potential has been explored only to a limited extent.
2. We present BatRack, a multi-sensor device that combines ultrasonic audio recordings, automatic radio telemetry and video camera recordings in a single modular unit. BatRack facilitates the individual or combined scheduling of sensors and includes a mutual triggering mode. It consists of off-the-shelf hardware and both its hardware blueprints and the required software have been published under an open license to allow scientists and practitioners to replicate the system.
3. We tested the suitability of radio telemetry and audio sensors as camera triggers and evaluated the detection of individuals in video recordings compared to radio telemetry signals. Specifically, BatRack was used to monitor the individual swarming behaviour of six members of a maternity colony of Bechstein's bat. Preliminary anecdotal results indicate that swarming intensity is related to reproductive state and roost switching.
4. BatRack allows researchers to recognize individual bats and monitor their behavioural patterns using an easily deployed and scalable system. BatRack is thus a promising approach to obtaining detailed insights into the behavioural ecology of bats.

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## KEYWORDS

automatic radio tracking, bats, behavioural ecology, camera traps, multi-sensor, passive acoustic monitoring

## 1 | INTRODUCTION

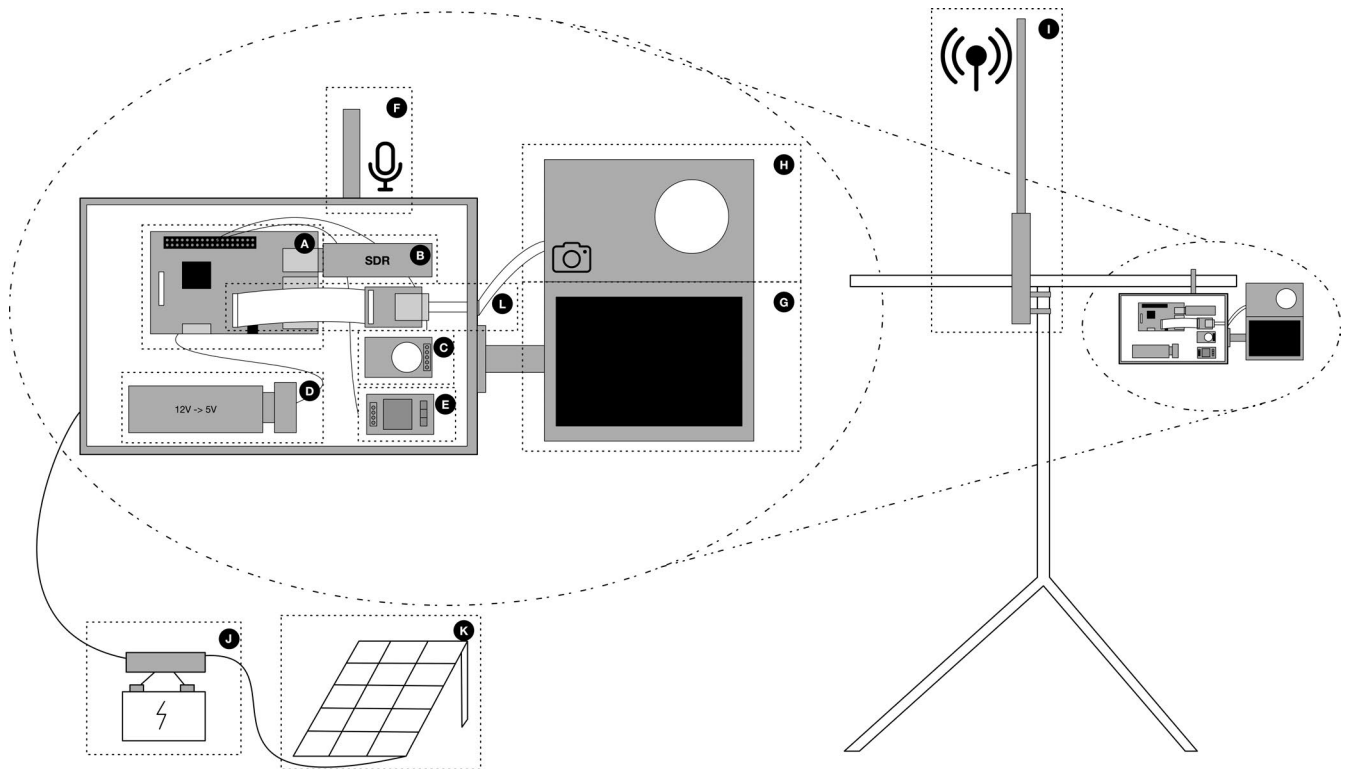
Many of the important findings and principles of ecology and conservation biology have been derived from behavioural observations (Clutton-Brock & Sheldon, 2010), but these are difficult to obtain for small wildlife (Kelly, 2008). To further close knowledge gaps, the constraint of ecological surveys between grain and extent must be further resolved. This requires automatic, cost-effective and data-efficient (i.e. triggered) observation systems that provide comprehensive sensor combinations and enable automatic observation at the individual level.

Video recordings are often used to observe the behaviour of individuals (Caravaggi et al., 2017), but for small species camera traps are effective only over short distances (Randler & Kalb, 2018). The observation of bats is particularly difficult due to their nocturnal lifestyle in often richly structured habitats. Instead, recordings of echolocation calls are frequently used to monitor the presence/absence of bats (Milchram et al., 2020). These acoustic signals, with their comparatively long range (Enari et al., 2019), can serve as triggers for visual sensors. The combination of audio and video

can additionally support the interpretation of the data (Buxton et al., 2018).

However, recognizing individuals on images, particularly small and nocturnal species or species that lack unique visually detectable features, is challenging (Rowcliffe et al., 2008), as is the recognition of individuals based on acoustic recordings (Stowell et al., 2019). By contrast, the automatic tracking of bats using lightweight VHF radio transmitters offers several advantages (Gottwald et al., 2019; Kays et al., 2011; Taylor et al., 2017): (a) VHF signals can be used as triggers for other sensors and (b) they may support the recognition of individuals in video sequences based on comparisons of the VHF signal patterns with the movements observed in the video.

To combine the desirable features of audio and video monitoring, we developed BatRack, a modular observation system that integrates audio, video and automatic VHF radio tracking in a single unit. The three recording technologies can be used separately, simultaneously or in mutual trigger mode, and the corresponding configuration scheduled and switched automatically. BatRack's hardware is assembled from off-the-shelf components and its



**FIGURE 1** Hardware components of BatRack: (a) Raspberry pi mini computer, (b) rtl-sdr dongle, (c) real time clock or LTE stick (d) 12V to 5V converter with USB power supply, (e) KY-019 relay, (f) ultrasonic microphone, (g) IR spotlight, (h) Raspberry pi camera (NoIR or HQ-camera with removed IR filter), (i) omnidirectional antenna, (j) 12 V battery, (k) solar panel

design and the required software have been published under a GNU GPL 3.0 license.

In the following, we present BatRack's hardware and software, evaluate the suitability of its audio and VHF sensors in triggering the camera, and test the potential of VHF recordings in the identification of individuals in videos, in a case study of the dawn-swarming behaviour (Kunz, 1982) of Bechstein's bat *Myotis bechsteinii*. To date, only a few studies have examined this behaviour in detail (Nado & Kaňuch, 2013). Using BatRack's combined sensor approach, we can provide new insights based on individual-related information about the reproductive state and an individual's decision to change roost sites during the night.

## 2 | MATERIALS AND METHODS

### 2.1 | The BatRack system

BatRack combines a core computation component with three sensor units (audio, video and VHF) and tailored analysis modules. Scientists and practitioners can easily assemble, configure and extend the system. Moreover, BatRack is inexpensive (~650€ without a power supply), easily repaired using commodity off-the-shelf (COTS) components (Figure 1), and uses free and open source software (FOSS). In addition, it is configurable with respect to the attached sensors as well as their recording ranges, time-based scheduling and mutual trigger mode. A detailed description of the hardware and software modules,

including product specifications and blueprints, can be found at the BatRack webpage (<https://nature40.github.io/BatRack/>).

For easy deployment, the software comes as a customized Raspberry Pi OS image bundle called BatRackOS (<https://github.com/Nature40/BatRackOS/releases/>), which was built using PIMOD (Höchst et al., 2020).

The audio module (Figure 2a) is implemented using *pyaudio* for audio data retrieval and *numpy* for further audio processing and bat call detection. The sampling rate depends on the hardware (e.g. 384 kHz for Dodotron Ultrasonic 384k). The camera analysis module (Figure 2b) uses the RPi Camera Web Interface software (<https://linux.org/RPi-Cam-Web-Interface>), which allows fast shutter speeds, concurrent camera access and automated exposure settings. Camera recordings are obtained in single image or continuous mode (max 90 frames/s) depending on user-defined settings.

The VHF analysis module (Figure 2c) uses the signal detection algorithm described by Gottwald et al., 2019. When a new signal is received, its strength and duration are evaluated such that remote and noisy signals are filtered out. All other signals are classified as active (i.e. flying) or inactive (i.e. resting; Kays et al., 2011). A bat is inactive if a standard deviation in signal strength  $<2$  is detected over at least 30 s, and active otherwise (Figure 3). If the VHF signals are used to trigger audio or video recordings, only time periods with active signals are written to memory, thus saving storage space and reducing the number of recordings that must be analysed. The operational modes of the analysis modules can be scheduled and configured individually.

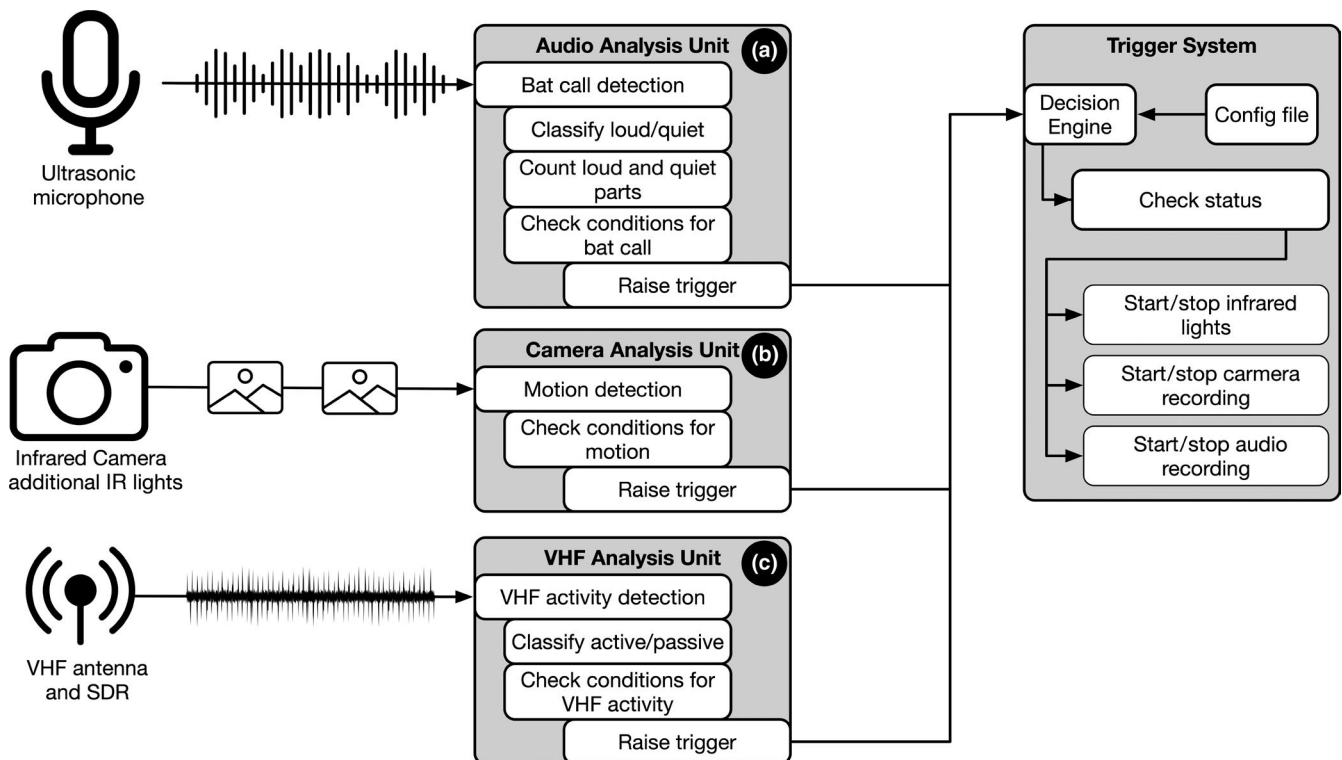
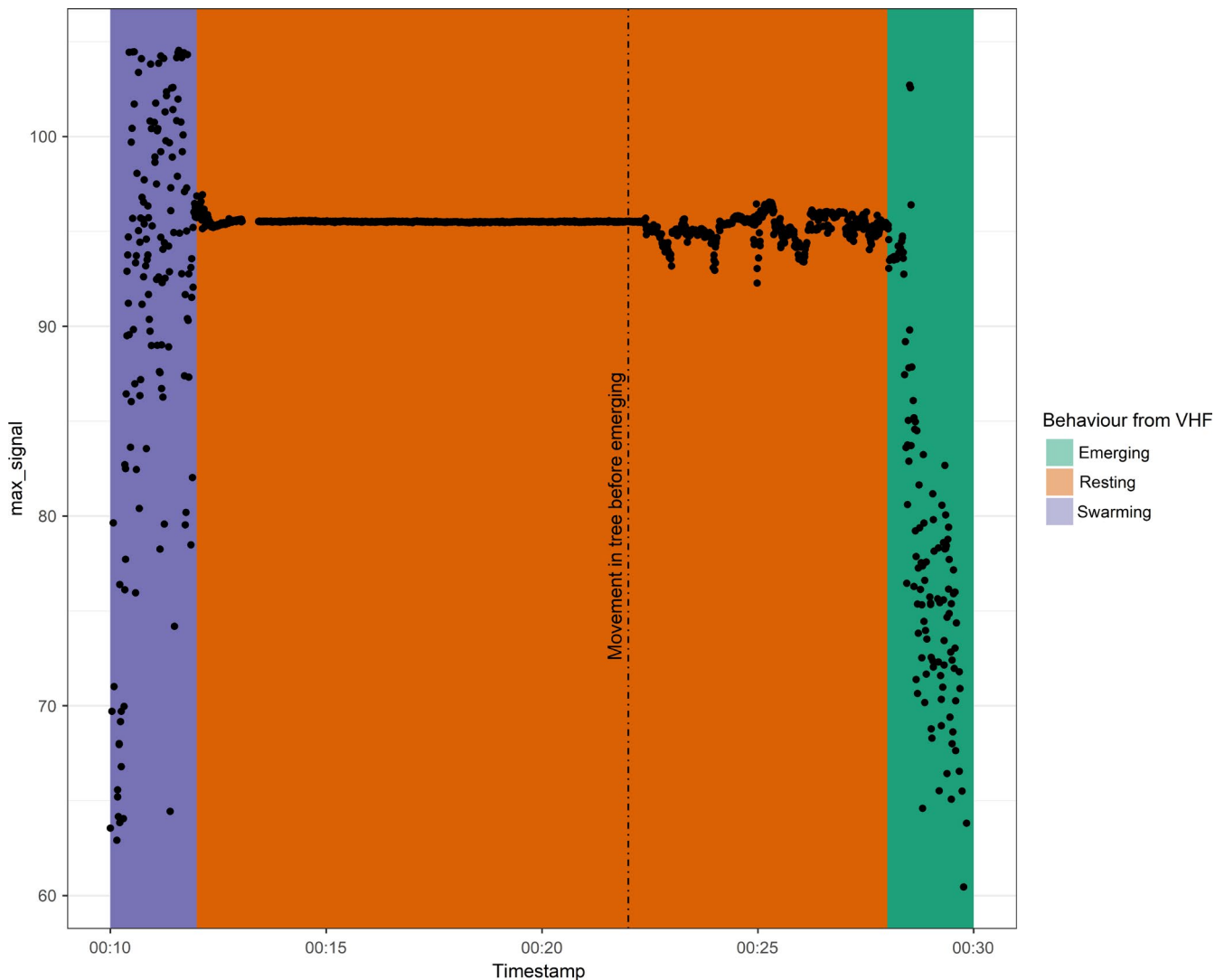


FIGURE 2 Analysis units of BatRack: (a) audio analysis unit (AAU), (b) camera analysis unit (CAU), (c) VHF analysis unit (VAU)



**FIGURE 3** VHF signal patterns in relation to the different modes of behaviour. Swarming (purple), passive (orange), emerging from roost (green)

## 2.2 | Audio-triggered video recordings

The suitability of passive ultrasonic audio observations for triggering video recordings of bats was tested by placing BatRack in front of a known roost of Bechstein's bats *Myotis bechsteinii* for one night. The use of highly sensitive settings (10 dB, 15 kHz) resulted in the triggering of video and audio recordings for 2 s approximately every 10 s. Audio recordings were visualized using BatScope (Obrist & Boesch, 2018) and classified as Bechstein's bats, other bats or no bats. Video sequences were manually screened for bats, and the ratio of simultaneous audio and video detections of bats served as the test variable.

To optimize the trigger parameters for the detection of Bechstein's bats, the recorded audio files were postprocessed using the trigger algorithm of the audio analysis unit. All possible combinations in the range of 15–50 kHz for the frequency threshold and 15–50 dB for the sound-pressure threshold were tested. All audio recordings classified as Bechstein's bat calls were treated as true positives; all other bat calls were excluded from the training dataset.

The maximum F1 score, which is the harmonic mean of precision and recall, was used to select the parameter combination that best minimized false positives while correctly identifying most true positives.

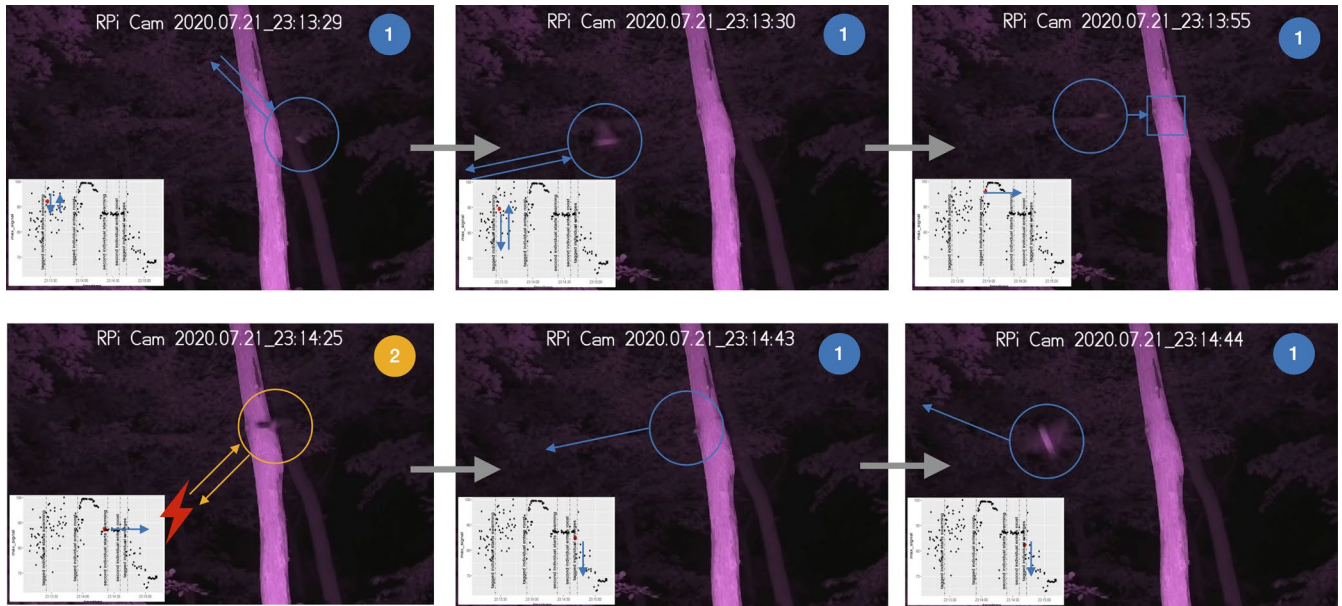
## 2.3 | VHF-triggered video recordings and individual-related behavioural patterns

To test the suitability of the VHF recordings in camera control and of the VHF signal strength in inferring behaviour, three pairs of Bechstein's bats from the same maternity colony were captured with mist nets between June and July 2020 and fitted with VHF tags. All females, except individual h172498, were in the expected reproductive state at the time of capture (Table 1). To monitor the bats, three BatRacks were placed in front of known roosting trees at a distance of 5–15 m for a total of 30 nights between June and August 2020.

To determine the suitability of VHF receptions in triggering video recordings of tagged individuals, the ratio of expected

**TABLE 1** Studied female Bechstein's bat individuals and their pair assignments

ID	Reproductive state	Pair	Capture date	VHF frequency
h146480	Pregnant	Pair1	08.06.2020	150.187
h172494	Pregnant	Pair1	08.06.2020	150.128
h172498	Not reproducing	Pair2	23.06.2020	150.172
h146482	Lactating	Pair2	18.06.2020	150.199
h146486	Postlactating	Pair3	15.07.2020	150.199
h146488	Postlactating	Pair3	15.07.2020	150.156

**FIGURE 4** Identification of a tagged individual. The VHF signal shows strong fluctuations during swarming (up left and mid). The signal fluctuations decrease significantly after the bat enters the tree (up right, down left). Shortly after a second individual enters the tree (down mid), the tagged bat emerges from the tree (down right)

captures based on VHF patterns to manually screened, actual video captures of at least one visible bat was used as the test variable. To investigate the potential of individual measurements to infer behavioural patterns, in this case swarming and emerging, the VHF data were analysed manually. Swarming was defined as both a signal pattern indicating an active bat and a signal strength above a threshold of  $-20$  dBW for at least 30 s (Figure 3, purple). This corresponded to the continuously flying of a tagged individual in close proximity to the sensor unit. Emerging was defined as a resting phase immediately followed by a strong signal, which in turn dropped off very quickly and did not stabilize immediately (Figure 3, green).

The observed behaviour of the bats was manually labelled as swarming if the recorded video sequences revealed an individual that moved back and forth in the area of the roost, if the individual briefly approached the tree, or if it left the roost after a short entry. Exits that were not directly followed by re-entry or swarming were classified as emerging.

To determine whether the video-captured bats could be identified as the tagged individuals, the VHF signal patterns and the corresponding movement patterns in the video were compared. Exemplary VHF

data and video frames are shown in Figure 4. The full video sequence and animated VHF data are provided at the BatRack webpage.

Unless otherwise stated, all analyses were performed using R (R Core Team, 2020).

### 3 | RESULTS

#### 3.1 | Audio trigger performance

During the test night, 3,317 audio-triggered audio and video recordings with an average length of 2 s were collected. Bats could be manually identified on 170 video (5.1%) and 663 audio (20%) recordings. From the latter, 272 recordings (41%) most likely originated from Bechstein's bats. For 166 of the 170 (97.6%) videos, a bat call was recorded simultaneously; in 160 cases (94.1%), the call was classified as that of a Bechstein's bat.

After all files with calls that could not be assigned to Bechstein's bats were removed and files without bat calls retained as true negatives, the remaining 2,929 files were processed to determine the optimal trigger parameters. The optimal combination of frequency and volume

threshold based on the maximum F1 score (0.91) was 15 dB and 38 kHz. With this combination, 235 out of 274 files containing Bechstein's bat calls (sensitivity = 0.858) were correctly identified; only 5 out of 2,655 negatives were falsely identified as positives (specificity = 0.998).

### 3.2 | VHF trigger performance

In total, 205 video recordings were captured that matched the VHF sequences classified as swarming or emerging. Of these, 130 (63%) were considered to show swarming and 75 (37%) emerging. Manual screening of the footage revealed one or more bats on 170 of the 205 (83%) sequences. Swarming was successfully detected in 93% of the sequences in which swarming was expected (122 out of 130), and emerging in 65% of the sequences (49 out of 75).

From the 170 (91%) video detections of a bat, in 155 the bat could be identified as the tagged individual with a very high probability, based on comparison of the movement pattern with the VHF signal strength. Among the 49 emerging and 130 swarming events, this was the case for 47 (96%) and 108 (83%), respectively.

### 3.3 | Individual behaviour patterns

Pregnant and postlactating bats (Figure 5; pairs one and three) did not show any apparent differences in their swarming and resting patterns, either between individuals of a pair or between pairs. All four individuals showed a higher swarming frequency on the night of the roost change and on the following night. During the latter, repeated swarming sequences and resting phases at the abandoned tree occurred. The lactating female (Figure 5; pair two, h146482), showed a higher frequency of swarming behaviour and resting periods than observed in the nonreproducing female (Figure 5; pair 2).

## 4 | DISCUSSION

A prerequisite for understanding dynamic natural environments as socio-ecological systems is data collected using highly automated monitoring systems. Recent developments have shown that the integration of (multiple) sensors and technologies in data acquisition and analysis can provide deep insights into the ecology of different species (Greif und Yovel, 2019; Ripperger et al., 2020; Schlägel et al., 2019; Toledo et al., 2020). BatRack offers a highly promising solution in the observation of bats. With its modular COTS design, BatRack can be readily built and easily maintained, allows individual configurations and extensions, and enables both flexible scheduling and the combination of measurements.

BatRack yields reliable occurrence information based on audio or VHF recordings. The latter can be used in the retrieval of basic behavioural information even from a single, nondirectional VHF receiver. Especially for small bat species, the use of either VHF or audio to trigger a video unit results in more energy- and storage-efficient video capture than allowed by purely schedule-based recording. A high

detection probability and a substantial reduction in false positives are ensured by applying targeted trigger parameters to the audio unit. Triggering based on the VHF signal results in an even better performance with bats captured almost all the time when one of the tagged bats triggered the recording. In our study, valuable video recordings were obtained even for bats flying up to 15 m away from the sensor.

Our case study on the behaviour patterns of Bechstein's bats illustrates the potential of BatRack. The observations provide first anecdotal indications of an association of increased swarming activity with a change of roost (pair one, three) and weaning of the pup (pair two). However, the advantage of information acquired at the individual level comes at the price of having to tag the animals. Furthermore, the identification of an individual is more difficult if several tagged individuals with similar levels of activity are recorded simultaneously.

The application possibilities of BatRack are manifold. Observations that were previously only possible in the laboratory can be obtained in natural habitats. BatRack is best suited for studies where the observation of bats is linked to a specific and small area (e.g. hibernation roosts, maternity colonies, specific resource occurrences). The focus here is on the study of social behaviour between animals or the use of resources. The mobility of BatRack also makes it possible to complement laboratory studies with field experiments (e.g. changes in resource availability). Moreover, while behavioural contexts can often be inferred from vocalizations, reference recordings are missing for many species (Teixeira et al., 2019). This deficiency can be addressed by BatRack, which can be used to collect visual ground truth of the behavioural significance of vocalizations. Thus, BatRack is a promising building block to close knowledge gaps regarding bat behaviour and to develop and evaluate conservation measures.

### ACKNOWLEDGEMENTS

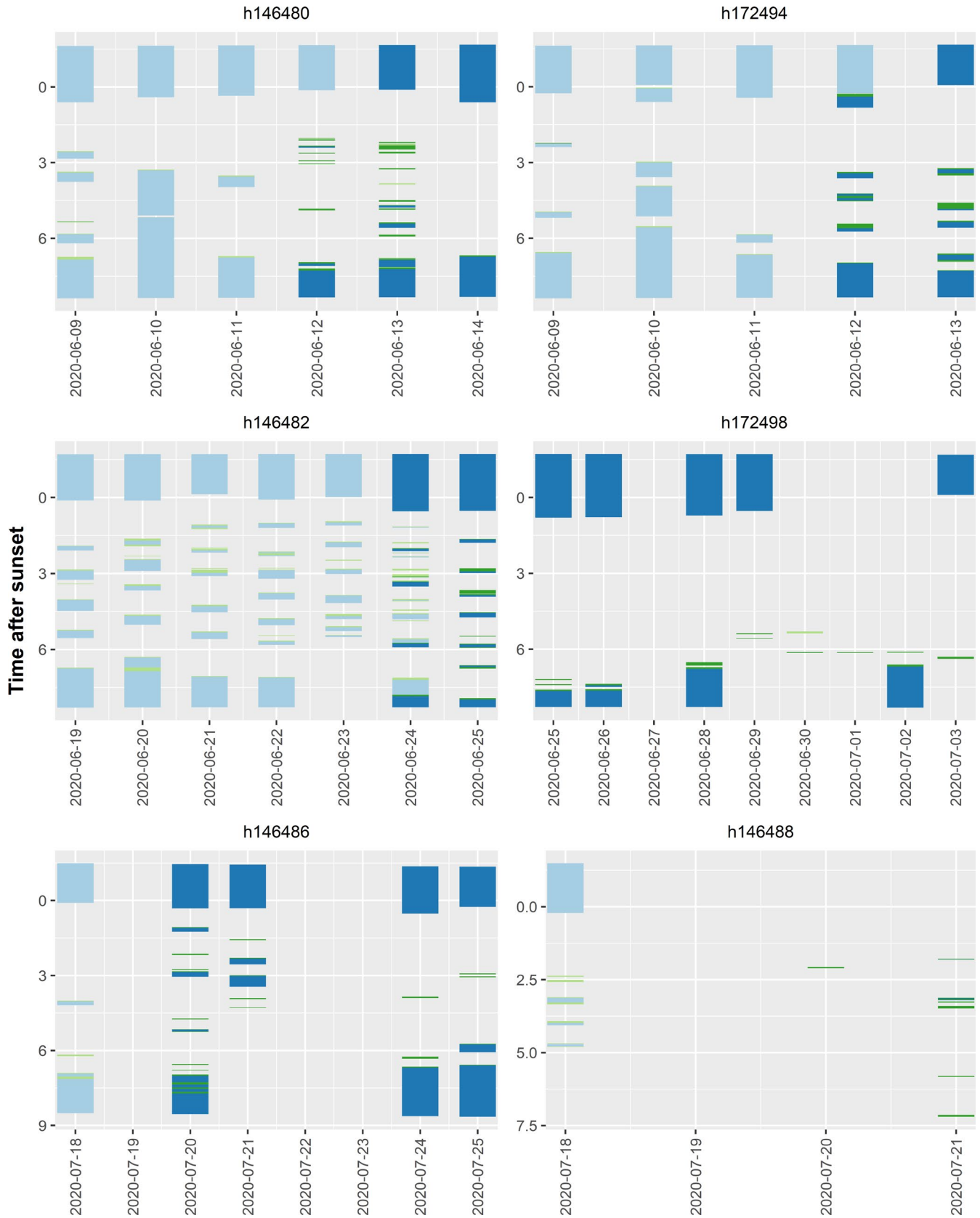
The system was deployed at Marburg Open Forest, the open research and education forest of the University of Marburg, Germany. The research was funded by the Hessen State Ministry for Higher Education, Research and the Arts, Germany, as part of the LOEWE priority project Nature 4.0—Sensing Biodiversity (<https://uni-marburg.de/natur40>).

### CONFLICT OF INTEREST

The authors of this manuscript certify that they have no conflict of interest in the subject matter or materials discussed in this manuscript.

### AUTHORS' CONTRIBUTIONS

J.G. and P.L. contributed equally to the realization of the presented research; J.G. proposed, planned, coordinated and conducted the field campaign and led the writing of the manuscript; J.G. and P.L. designed the hardware and defined the features of the software; P.L. wrote the source code and guided rapid-prototyping in the field; J.H. and P.L. refactored the source code and tested the refactored software; J.M., L.L., T.R. and B.N. deployed BatRack in the field; J.M. and L.L. screened the videos and B.N. analysed the audio recordings; B.F., N.F. and T.N. critically revised the different versions of the system and contributed to its optimization. All authors contributed to the writing of the manuscript.



**FIGURE 5** VHF-signal-derived behavioural patterns of Bechstein's bat pairs. Blue = inactivity, green = swarming. Gradations in the respective colour scale indicate the roost used for resting (Tree A = lighter blue, Tree B = darker blue) or for swarming (Tree A = lighter green, Tree B = darker green)

## PEER REVIEW

The peer review history for this article is available at <https://publons.com/publon/10.1111/2041-210X.13672>.

## DATA AVAILABILITY STATEMENT

All data used for the evaluation of BatRack is open access and available via data\_UMR, the long-term data repository of the University of Marburg (<http://dx.doi.org/10.17192/fdr/67>).

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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