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Field tests of small autonomous recording units: an evaluation of in-person versus automated point counts and a comparison of recording quality

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ABSTRACT

The proliferation of small autonomous recorders makes it easier than ever to sample terrestrial acoustic animals and soundscapes. I conducted a comparison of four small recorders to evaluate their performance in a field setting: Wildlife Acoustics Song Meter Mini; Wildlife Acoustics Song Meter Micro; Open Acoustics Audiomoth; and Cornell SwiftOne. I address two questions: (1) How do in-person point counts compare to recorder-based point counts using these small autonomous recorders? (2) How does the quality of the recordings compare across these small autonomous recorders? To evaluate the performance of the recorders in point counts, I conducted in-person and recording-based point counts at ten locations. Each of the recorders performed similarly well at point counts, producing comparable estimates of species richness, although all of the autonomous recorders under-estimated species richness. To evaluate recording quality, I conducted a sound transmission test, broadcasting and re-recording sounds. Recorders varied in their frequency response above 12 kHz, but showed only subtle differences in the frequency response at frequencies below 12 kHz. I conclude that each of these types of small recorders provide bioacousticians with useful tools for conducting point counts, and for passive monitoring of animal sounds, with only subtle differences across the investigated models.

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Introduction

Innovations in recording technology drive developments in bioacoustic research on animal ecology, behaviour, and conservation. The invention of portable tape recorders in the mid-twentieth century gave rise to field sampling of the sounds of wild animals, including species such as the Kaua'i O'O (*Moho braccatus*) and Bachman's Warbler (*Vermivora bachmanii*), whose voices might otherwise be lost to extinction (Barnes 1954; Conant et al. 1998). Studies of wild animals expanded with the advent of field-portable recorders, enabling biologists to gather data from recordings stored on magnetic tape and, later, digital media (Baptista and Gaunt 1994; Pavan et al. 2022). Today, digital recorders have ushered in a new era of field recording, characterised by lightweight and easy-to-transport recorders accompanied by increasingly affordable digital storage

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media. Recent developments in portable autonomous recorders have resulted in an explosive increase in digital studies of animal species richness and population size, investigations of rare and endangered animals, bioacoustic indices of soundscapes, and the collection of long-term bioacoustic archives (Blumstein et al. 2011; Shonfield and Bayne 2017; Alcocer et al. 2022).

As with most electronics, autonomous recorders have undergone a process of miniaturisation. Today's recordists can choose between autonomous recorders that are much smaller than previous models. Whereas early models of autonomous recorders were heavy, weighing 3 kg or more, many new autonomous recorders are less than 1 kg, with a smaller form factor than the recorders used during the first two decades of the 21st century. These new small and lightweight digital recorders offer many advantages: they are less expensive than most previous digital recorders, they are easier to transport into the field, and they allow recordists to collect more recordings over broader areas. Several manufacturers produce popular small autonomous recorders: the Song Meter Mini and the Song Meter Micro are produced by Wildlife Acoustics; the AudioMoth is produced by Open Acoustics; and the SwiftOne recorder is produced by Cornell University's Centre for Conservation Bioacoustics. Additional small recorders are available, including recorders from Frontier Labs and Titley Chorus, and other models of recorder from Open Acoustics, as well as custom-built recorders using Raspberry Pi computers, although these recorders are less commonly used than the aforementioned recorders that I evaluate here (Metcalf et al. 2023).

With the proliferation of new small autonomous recorders – i.e. recorders weighing approximately 1 kg or less – it is worthwhile to test their performance in typical field contexts that are important to bioacousticians, ecologists, and conservationists, and to compare and contrast recordings collected with different autonomous recorders and evaluate their performance relative to in-person survey methods. In this study, my goal was to compare four widely used, commercially available small autonomous recorders in the context of field studies of terrestrial animals, with a focus on birds. I conducted two field tests. First, I conducted point counts to compare field recordings to in-person point counts using these small autonomous recorders. Second, I broadcast and re-recorded sounds in the field to compare the sound quality of recordings collected with these small autonomous recorders. I was motivated by a desire to better understand how these recorders perform in the field, and to offer insight to other researchers interested in small digital recorders.

Methods

I compared small autonomous recorders by collecting field recordings at Bowdoin Scientific Station on Kent Island (44°35'N, 66°46'W) in the Bay of Fundy, New Brunswick, Canada in June of 2022. I used five types of autonomous recorders (Figure 1(a); comparison of details of the recorders summarised in Table 1): (1) Wildlife Acoustics Song Meter Mini, recording at a sampling rate of 48 kHz and the default microphone gain of 18 dB. Song Meter Minis are typically sold as monaural recorders with a single detachable microphone; I purchased a stereo recorder with an additional microphone for use in other research projects, but did not use the second microphone in the recordings analysed here, to facilitate

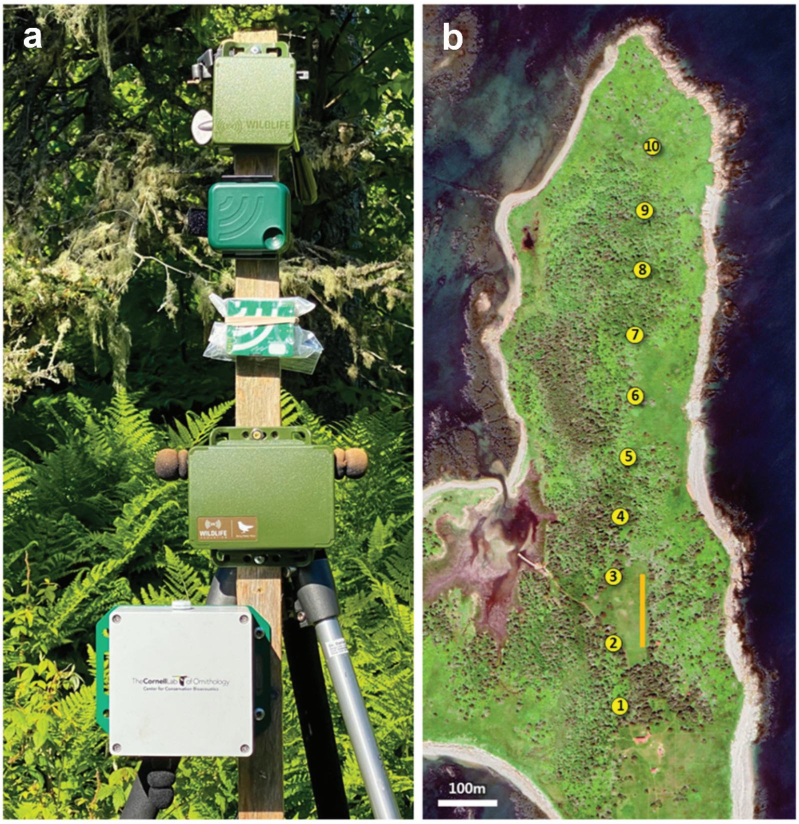

Figure 1. a Photographs of five small autonomous recorders tested in a field-based study of point counts and sound recording. From top to bottom: a Wildlife Acoustics Song Meter Micro; an Audiomoth in a plastic protective case; an Audiomoth in a plastic bag; a Wildlife Acoustics Song Meter Mini; and a Cornell Lab of Ornithology SwiftOne. b Map of ten point count locations (yellow dots, each separated by 100 m) and the recording transect location (the orange line, 100 m in length) on the northern half of Kent Island, New Brunswick, Canada, at the Bowdoin Scientific Station.

comparison to the other monaural recorders. (2) Wildlife Acoustics Song Meter Micro, recording at a sampling rate of 48 kHz and the default microphone gain of 18 dB. (3) Open Acoustics Audiomoth, recording at a sampling rate of 48 kHz with the default microphone gain of ‘medium’. Audiomoths are typically deployed in a waterproof plastic case or in a waterproof plastic bag. I therefore used two Audiomoths in all of my recordings: (3a) an Audiomoth in a green waterproof plastic case manufactured by Open Acoustics (case model: IPX7); (3b) an Audiomoth in a transparent, zipper-sealed, polyethylene plastic bag (bags were purchased with the recorder from Open Acoustics). (4) Cornell SwiftOne recorder, recording at a sampling rate of 48 kHz and the default microphone gain of 18 dB. I used a SwiftOne recorder with a green metal bracket for mounting on trees. I operated all of the recorders with rechargeable Nickel Metal Hydride (NiMH) batteries. I did not exhaust any batteries during the course of these trials and I did not compare the battery life of the recorders.

Table 1. Comparison of key features of the small autonomous recorders used in this study.

Recorder	Size	Weight (with batteries)	Power	Storage	Controller	Operating Systems	Recording Mode	Microphone type	Microphone model
Wildlife Acoustics Song Meter Mini	16.8 × 12.3 × 3.6 cm	290 g	4 × AA	SD card	Mobile phone or tablet	iOS and Android	Mono or Stereo	Detachable membrane microphone	Wildlife Acoustics SMMini Microphone
Wildlife Acoustics Song Meter Micro	10.1 × 7.4 × 2.8 cm	195 g	3 × AA	micro SD card	Mobile phone or tablet	iOS and Android	Mono	Non-detachable MEMS microphone	Wildlife Acoustics SMMicro Microphone
Open Acoustics Audiomoth (in Plastic Case)	5.8 × 4.8 × 1.5 cm	190 g	3 × AA	micro SD card	Computer	Windows, Mac, Linux	Mono	Non-detachable MEMS microphone	Knowles SPU0410LR5H-QB
Open Acoustics Audiomoth (in Plastic Bag)	5.8 × 4.8 × 1.5 cm	185 g	3 × AA	micro SD card	Computer	Windows, Mac, Linux	Mono	Non-detachable MEMS microphone	Knowles SPU0410LR5H-QB
Cornell Swift One Recorder	20.3 × 12.7 × 10.1 cm	1080 g	4 × D plus coin cell	SD card	Computer	Windows	Mono	Detachable membrane microphone	PUIaudio POW-1644 L-B-LW100-R

Point counts

I conducted in-person point counts between 0800 h and 1000 h on 12 June 2022. This was a sunny day with light wind. During the in-person point counts, I collected recordings from all of the devices simultaneously using all of the automated recorders positioned directly beside me. The recorders were mounted on a single post, one atop the other at a height of 1.2 to 1.8 m, with the post supported by a tripod (Figure 1(a)). I conducted point counts at ten locations within forest and forest-field-edge habitat, starting in the forest near the Bowdoin Scientific Station's main building and continuing in a transect northwards along one of the station's main trails (Figure 1(b)). Each point was separated by a distance of 100 m, measured using a hand-held Global Positioning System (Garmin GPS 60CSx). Point counts lasted for five minutes, following typical protocols in Canada for the Breeding Bird Survey (Dunn et al. 2000; Hudson et al. 2017). I broadcast a tone at the start of each point count to standardise the start time of the in-person count and, later, the count data collected from the recording.

In the laboratory, many months after the field season, I conducted point counts using the field recordings. The type of recorder was anonymised when conducting analyses (see details of my anonymising procedure below). I used Audition (Adobe Inc., San Jose, USA) to listen to each recording exactly once, in its entirety, without pausing or stopping. I did not visualise the recordings as waveforms or spectrograms; I conducted the lab-based point counts only by listening to the recordings. I listened to the recordings using Bose QC45 headphones with the noise cancelling feature enabled. I analysed only five recordings on any given day, to minimise any bias due to listener fatigue. I analysed the recordings in random order, using a random number generator to select which recording I would analyse next.

I chose to analyse the recordings myself, rather than having different people analyse the acoustic recordings, so that variation in observer ability (Sauer et al. 1994; Farmer et al. 2012) would not be a factor in the comparisons between in-person and recorded point counts. I chose to analyse the recordings by listening in real time, rather than using BirdNet or other automated approaches, and rather than manually annotating spectrograms, so that variation in software would not be a factor in the comparisons. Given this approach, the focus of my comparison was the difference between hearing birds in person in the field, versus hearing birds in recordings in the lab using the different types of autonomous recorder, with the same listener in all cases.

All birds detected in the recordings were also detected during the field survey (see Results, below, for details), with one exception: in a single recording (1 out of 50) I detected a species in the recording dataset that I did not detect during the in-person point count at that site (a Red-breasted Nuthatch, *Sitta canadensis*, at point count location #9). For the purposes of determining the total number of species that were truly present at each location, I included all species detected during the in-person point counts plus the Red-breasted Nuthatch recorded at location #9.

Sound transmission test

To study the quality of recordings, I played back sounds from a loudspeaker and recorded the sounds simultaneously from all the automated recorders mounted on a single post at a height of 1.2 to 1.8 m, as in the point count recordings. I collected recordings between 0800 h and 0900 h on 14 June 2022. This was a cloudy day with little or no wind. The recordings were collected in a meadow called ‘North Field’ at Bowdoin Scientific Station, which is an open grassy field surrounded by mixed forest (Figure 1(b)). I used the exact same recorders for the recording transects as the point counts. In addition to the five automated recorders, I also recorded sounds with a Marantz PMD-660 digital recorder connected to a Sennheiser ME62/K6 microphone (microphone specifications: LINK). My intention was that this Marantz-with-Sennheiser would serve as a reference point to compare to the automated recorders.

Sounds were broadcast from an iPhone 11 connected via Bluetooth connection to a JBL Flip 5 loudspeaker mounted on a post at a height of 1.5 m. (The JBL Flip 5 loudspeaker has a power rating of 20 watts and relatively flat frequency response from 100 Hz to 5 kHz, with a decrease of approximately 5 dB in the frequency response at 5 kHz to 12 kHz, and a further decrease above 12 kHz.) I varied the distance between the loudspeaker and the recorders with distances-of-separation of 6.25 m, 12.5 m, 25.0 m, 50.0 m, and 100.0 m, using a tape measure marked with cm. At each distance I broadcast a set of sound stimuli three times, in an attempt to maximise the chance that the stimuli would be recorded at least once without being overlapped by other sound sources in the field. The position of the recorders was held constant, and the loudspeaker was moved to the five different playback distances. The volume of the loudspeaker was held constant throughout the sound transmission tests, at an intensity that approximated the natural amplitude of bird vocalisations based on my aural assessment in the field.

The playback stimuli consisted of synthetic sounds and animal recordings. To characterise the frequencies recorded by the different autonomous recording units, I created two synthetic stimuli. (1) I generated a series of 20 half-second tones played at frequencies descending from 20 kHz to 1 kHz, at 1 kHz intervals. I created these tones in Audition using sine waves with no frequency modulation, at an amplitude of −24 dB. (2) I generated an ascending tonal frequency sweep that covered a broad frequency range, rising from 0 Hz to 20 kHz over a period of 30 seconds. I created this frequency sweep in Audition using a sine wave, at an amplitude of −24 dB. I also broadcast a collection of different animal sound recordings to compare the recordings by the different recorders, each standardised to an amplitude of −1 dB in Audition. This collection of sounds came from a previous study from my laboratory (Mennill et al. 2012) and from my laboratory’s sound library (details in Appendix).

To compare recording quality across the autonomous recorders, I isolated the best-recorded set of descending tones and ascending frequency sweep for each type of recorder, selecting the recording at each distance with the lowest amount of overlapping background sounds. I repeated this process at each distance. I generated spectrograms of the descending tones in Syrinx-PC (FFT: 1024 Hz, Hanning) and noted which frequencies between 20 kHz and 1 kHz were recorded at each recording distance, maintaining the same gain of 0 dB on the spectrograms. To analyse the ascending frequency sweep, I applied a highpass filter at 250 Hz (sounds less than 250 Hz were not readily distinguishable from background noise, such as wind and sounds from motors from nearby lobster fishing boats, at farther playback distances), and I applied a lowpass filter at 12 kHz (tones at these frequencies were not easy to detect at the farther playback distances for some of the recorders; see Results). I then applied two triangular filters, using the lasso selection tool in Audition to select the triangular region 200 Hz above the frequency-modulated tone in each recording, and another to select the region 200 Hz below the frequency-modulated tone in each recording, and using the ‘amplify’ feature of Audition to reduce the background sound to 1%, allowing me to focus subsequent automated analyses solely on the frequency-modulated tone. I then used Avisoft SASLab Pro (R. Sprecht, Berlin, Germany) to measure the frequency and amplitude of the recordings of the frequency-modulated tone, applying the automated parameter measurements tool of AviSoft to measure the peak amplitude of the frequency modulated tone every 200 ms. I rejected amplitude measurements less than 10 dB, which appeared to be erroneous automated detections when viewed on the AviSoft sound spectrogram. I calibrated the amplitude of the recordings following the method outlined by Brumm et al. (2009), by recording tones at a known sound pressure level and known distance, measured with a calibrated Type II Casella CEL-24X Sound Pressure Level at the same position as each of the microphones (fast setting; A-weighting), and using the ‘calibrate’ feature of AviSoft. Recording with the default gain settings for all the recorders (described above), the recordings appeared to have comparable sound levels.

Anonymized analyses

To minimise opportunities for bias, I anonymised all of the files containing the field recordings prior to analysis, both for the point count recordings and the transect recordings. After downloading recordings and trimming all files to the same length, a colleague re-named the files with arbitrary names so that I could not identify the model of the recorders based on the recordings. I conducted all analyses with the anonymised data, and I wrote the paper with the identity of the recorders anonymised, and saved a date-stamped version of the manuscript. I then de-anonymised the data and adjusted the components of the manuscript that required me to specify which recorder was used.

Statistical methods

I compared the proportion of in-person species detections that were detected across the ten point count locations using a general linear mixed-effects model on the arcsin-transformed proportion data (raw data are shown in the figure), including recording location as a random effect, followed by a post-hoc Tukey test between the five types of recording device. This analysis was conducted in JMP (v16.2; SAS Institute, Cary, N.C., U.S.A.). For the sound transmission study, with only one replicate recording at each distance, I restricted my analysis to qualitative evaluations.

Results

In-person versus automated point counts

All five of the small autonomous recorders performed well at estimating bird species richness in comparison to in-person point counts, although all recording-based point counts underestimated species richness. A total of 18 species of birds were detected across all ten sites, with 8.4 ± 0.4 species per site detected during in-person point counts,

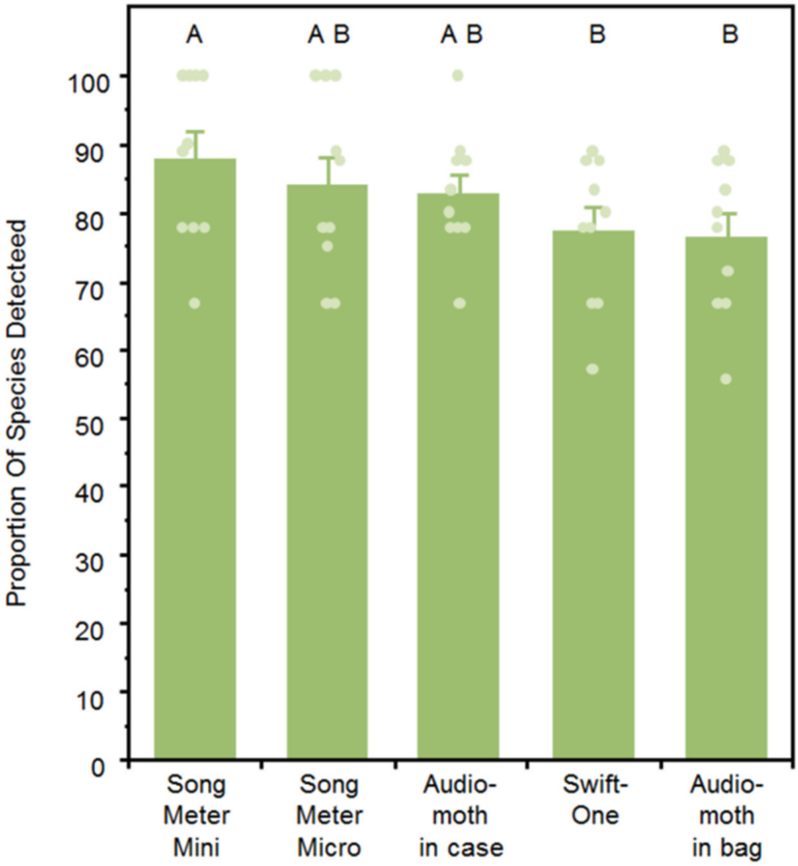

Figure 2. Comparison of point count data from five small autonomous recorders, relative to in-person point counts. Simultaneous point-counts and recordings were conducted at ten sites in the field, and recordings were analysed by the same recordist for comparison to in-person species richness; results from the five recorders are shown as the number of species detected in the recording, compared to the number of species detected during the in-person point count. Bars show means and whiskers show standard error; jittered points shown in light green show the raw data. Letters above bars show post-hoc results of a general mixed-effects model, where categories with different letters exhibit different proportions of species detected.

and 6.8 ± 0.2 species per site during recordings (means ± SEs). The autonomous recorders detected 77 to 88% of the species that were detected during in-person point counts (Figure 2). A mixed-effects model showed variation in the proportion of species detected (Table 2), and a post-hoc test showed that the Song Meter Mini detected the highest proportion (87.9%), the Swift-One and the Audiomoth in a plastic bag detected a lower proportion (77.3% and 76.5% respectively), with the Song Meter Micro and the Audiomoth in a plastic case detecting an intermediate level (84.0% and 82.7%, respectively) that was not different from the other levels (Figure 2).

Twelve to 23% of bird species that were detected during the in-person point count were missed by the automated recordings (Figure 2). Species that were most often missed in the recorded point counts were Alder Flycatcher (*Empidonax alnorum*; not detected in

Table 2. Details of linear mixed effect model explaining variation in the proportion of species detected by each recorder relative to in-person point counts, where the fixed effect is recorder type (five types of recorder) and the random effect is recording location (ten different locations).

Factor	Parameter estimate[a] ± SE	df	t	p
(Intercept)	2.34 ± 0.09	9,27	26.8	<0.0001
Recorder type (fixed effect)	0.25 ± 0.09	4,36	3.9	0.01
Location (random effect)	0.06 ± 0.04			

[a] parameter estimate is β for fixed effects and δ^2 for random effects.

27 of 35 recordings where it had been detected during in-person point counts), followed by Common Yellowthroat (*Geothlypis trichas*; not detected in 14 of 45 recordings), Canada Goose (*Branta canadensis*; not detected in 10 of 15 recordings), Savannah Sparrow (*Passerculus sandwichensis*; not detected in 9 of 15), and American Redstart (*Setophaga ruticilla*; not detected in 8 of 15 recordings). All five of these species were missed in recordings from all five types of recorders, and no one recorder appeared especially prone to missing any particular species.

Only one species of bird was detected in the recordings but missed during the in-person point count: a Red-breasted Nuthatch. Careful re-listening to the recording demonstrated that the bird was indeed present in the recording; it sang a quiet, species-typical song that was detected in the first few seconds of the recording, but I did not detect it in the field.

Sound transmission test

Recordings of synthetic tones ranging from 20 kHz to 1 kHz, at 1 kHz intervals, recorded at distances ranging from 6.25 m to 100 m, showed that all of the autonomous recorders recorded well at frequency ranges up to 12 kHz, but varied in how well they recorded sounds higher than 12 kHz (Figure 3). The Audiomoth recorders, when housed in a plastic bag or a plastic case, recorded tones up to 20 kHz that were visible in the spectrograms; sounds above 12 kHz became difficult to detect only at a recording distance of 100 m, and sounds below 12 kHz were detected at 100 m (Figure 3). The Song Meter Micro and the SwiftOne showed an intermediate capacity to record tones up to 20 kHz; sounds above 12 kHz became difficult to detect at a recording distance of 50 m, and frequencies up to 12 kHz were still detectable at 100 m (Figure 3). The Song Meter Mini and the Marantz-with-Sennheiser showed the weakest capacity to record in the upper frequency spectrum; tones above 12 kHz were noticeably lower in amplitude than tones below 12 kHz, even at a recording distance of 6.25 m, and sounds above 12 kHz became difficult to detect at a recording distance of 25 m and above (Figure 3).

I conducted a frequency analysis of the amplitude of a frequency sweep rising from 0.25 to 12 kHz, recorded at distances ranging from 6.25 m to 100 m. Analyses revealed that all recorders sampled most or all of the frequency sweep at all distances, but with variation in amplitude of the recorded signal across this frequency range. The recorded amplitude varied with frequency and showed slightly different frequency response curves across the six recorders (Figure 4). The Song Meter Micro, the Song Meter Mini, the SwiftOne, and the Marantz-with-Sennheiser showed higher amplitudes at middle frequencies, and lower amplitudes at low and high frequencies, whereas the Audiomoth

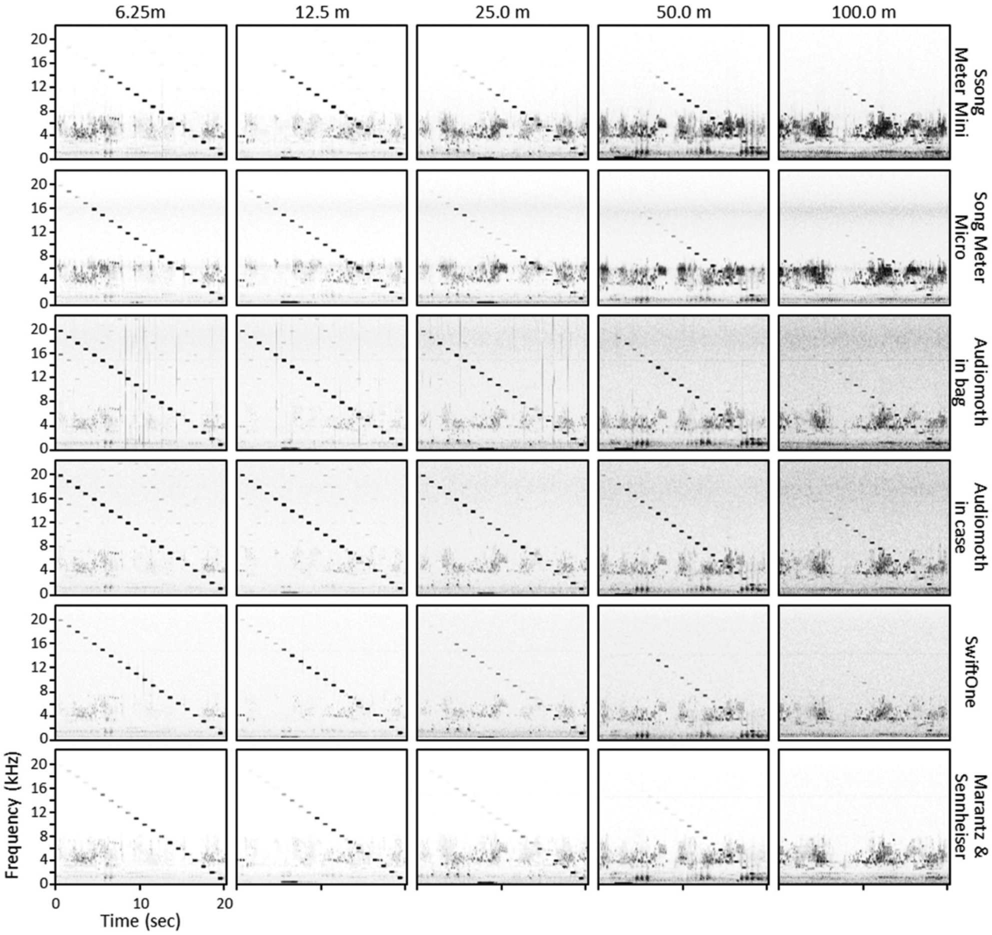

Figure 3. Sound spectrograms comparing 0.5-second pure tones broadcast from a high frequency of 20 kHz, descending by 1 kHz intervals, to a low frequency of 1 kHz, recorded with five small autonomous recorders, plus a non-autonomous recorder for comparison, at five distances from a loudspeaker: 6.25 m, 12.5 m, 25 m, 50 m, and 100 m. Non-target sounds from the recording area are present in the recordings, especially the recordings at greater distances from the loudspeaker.

recorders showed flatter curves that tended to record similarly at middle frequencies and high frequencies (Figure 4). The Song Meter Micro showed a slightly unusual pattern at middle frequencies, with higher amplitudes around 6 kHz (Figure 4). In theory, amplitude reduces by 6 dB with each doubling distance from the sound source, but, in practice, there was much variation around the amplitude of the recordings with doubling distance, including many frequencies where the amplitude was higher at a greater distances than lower distances (Figure 4).

Aural and visual comparison of the sound spectrograms of different types of animal sounds showed that all of the recorders generated recordings that allowed species identification. For example, recordings of both a high-frequency bird song (Chipping Sparrow, *Spizella passerina*; Figure 5) and a low-frequency bird song (Rufous-and-white Wren, *Thryophilus rufalbus*; Figure 6) had integrity at all recorded distances for all

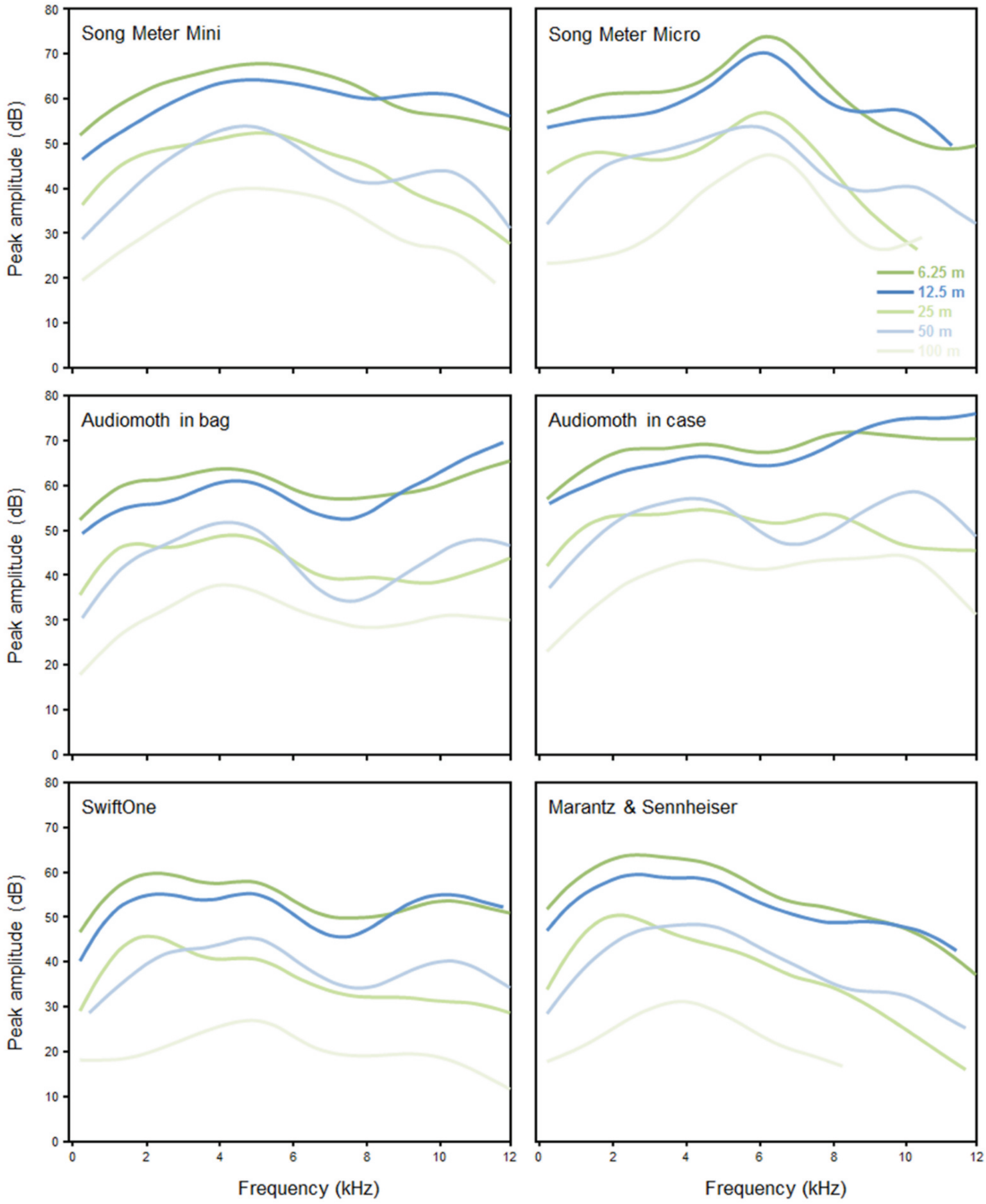

Figure 4. Peak amplitude versus frequency of a re-recorded frequency sweep that rises from 200 Hz to 12,000 Hz, recorded with five small autonomous recorders, plus a non-autonomous recorder for comparison, at five distances from a loudspeaker: 6.25 m, 12.5 m, 25 m, 50 m, and 100 m.

recorders. Several species of birds, including vocal sounds and non-vocal sounds, as well as several mammals and anurans, were all recorded well at most distances by all recorders, although overlapping sounds at the study site made recordings at 100 m difficult to detect across all types of recorder due to the masking effects of sounds at the recording location.

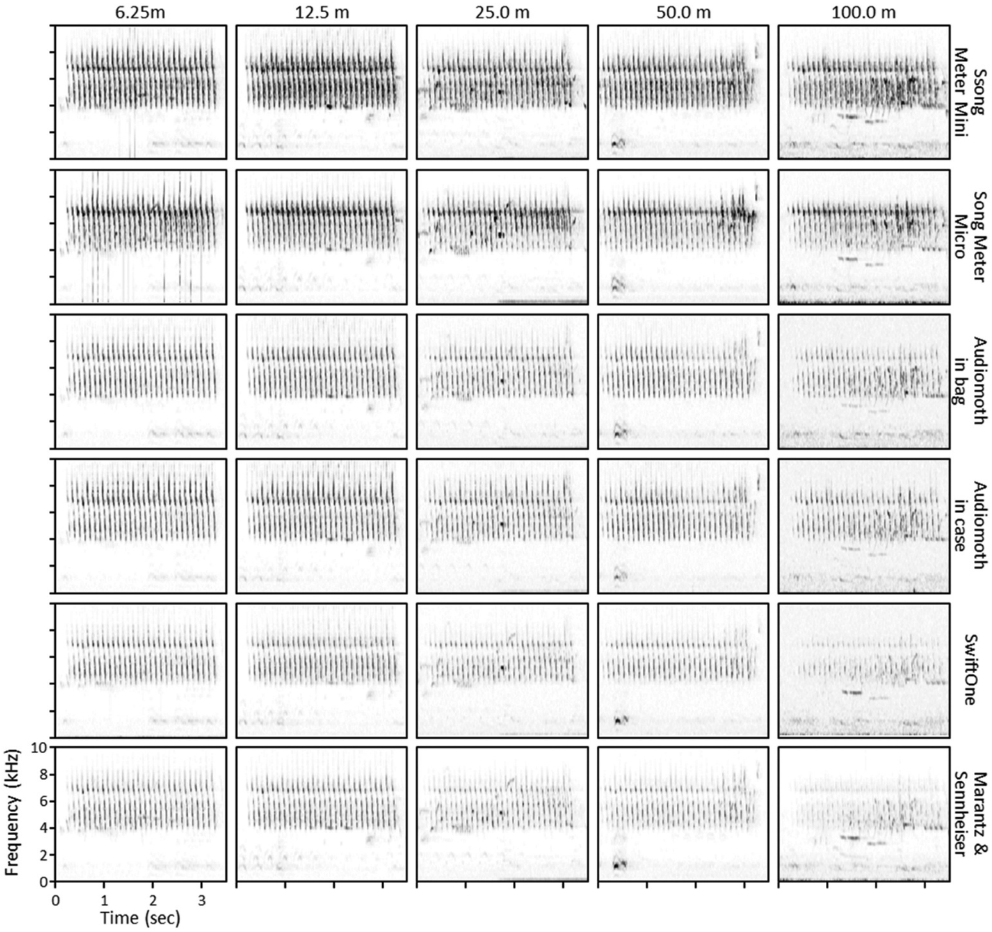

Figure 5. Sound spectrograms comparing an example bird song with a high frequency range, Chipping Sparrow (*Spizella passerina*), recorded with five small autonomous recorders, plus a non-autonomous recorder for comparison, at five distances from a loudspeaker: 6.25 m, 12.5 m, 25 m, 50 m, and 100 m. Non-target sounds from the recording area are present in the recordings, especially the recordings at greater distances from the loudspeaker.

Discussion

Increasingly small autonomous recorders represent a significant advance for passive acoustic monitoring because they are easy to transport and have a relatively low cost. It behoves us to evaluate their performance in real-world field settings, to confirm that small autonomous recorders generate reliable acoustic data. In a series of tests in a terrestrial wilderness recording context, I found evidence that new and widely-used small autonomous recorders produce reliable data in point counts of species richness of birds and in collecting field-based acoustic recordings. All of the small autonomous recorders performed similarly to each other in point counts, with the Song Meter Mini providing the most similar measurement to in-person point counts. All of the recorders under-estimated bird species richness, under-estimating species richness by 13 to 23%. When used to record

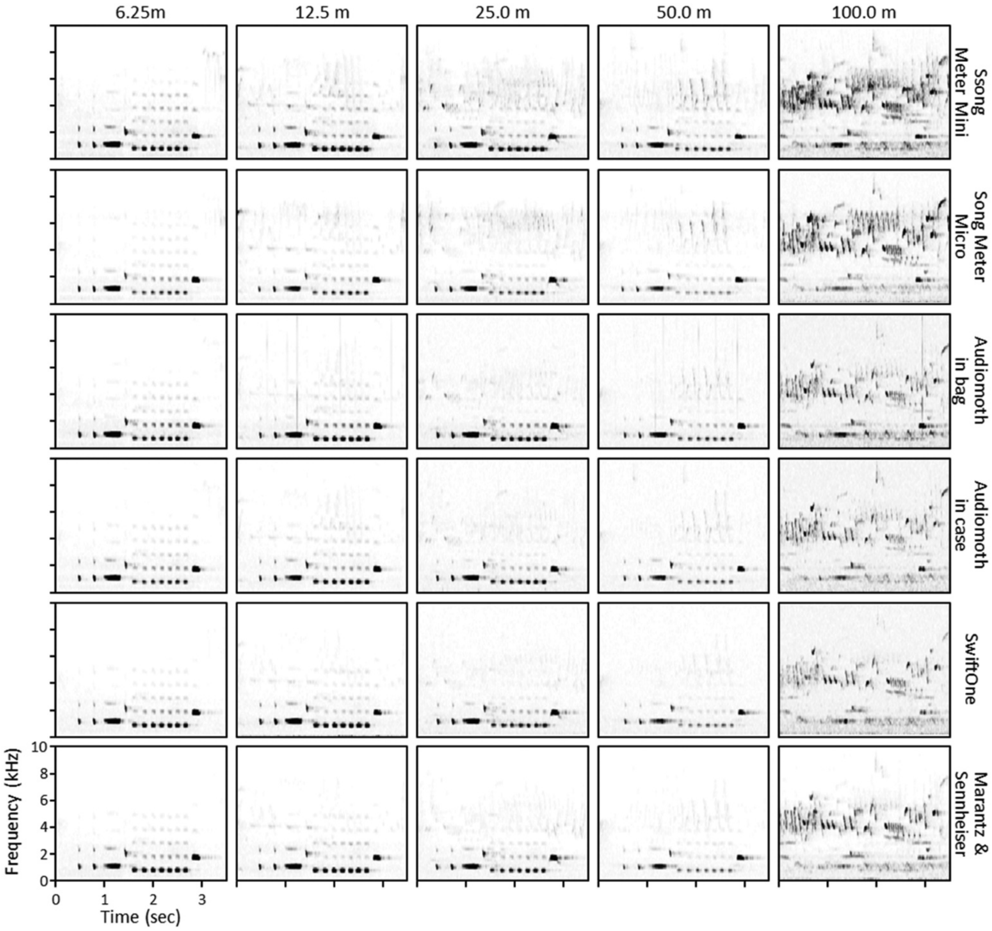

Figure 6. Sound spectrograms comparing an example bird song with a low frequency range, Rufous-and-white Wren (*Thryophilus rufalbus*), recorded with five small autonomous recorders, plus a non-autonomous recorder for comparison, at five distances from a loudspeaker: 6.25 m, 12.5 m, 25 m, 50 m, and 100 m. Non-target sounds from the recording area are present in the recordings, especially the recordings at greater distances from the loudspeaker.

sounds at variable distances from the sound source, all of the tested recorders performed well at recording sounds under 12 kHz at distances up to 100 m, whereas some of the recorders did not record sounds at 12 to 20 kHz, especially as the distance to the sound source increased. I conclude that all of the tested small recorders provide useful tools for conducting avian point counts and collecting wildlife recordings, and that these small devices are useful tools for field recording. Recordists should give careful consideration to the acoustic space that is sampled by these small autonomous recorders, and whether the recording limitations highlighted here, including an apparent limitation associated with recording at greater distances and higher frequencies for some devices, will influence recordings of the sound sources they are studying.

Performance in point counts

Many previous investigators have compared in-person point counts to recording-based point-counts (Shonfield and Bayne 2017; Darras et al. 2018), although not previously across the new, small autonomous recorders that I tested here. In an early comparison of an Amazonian forest bird community, tape recordings were shown to yield similar measurements of bird species richness to in-person point counts (Haselmayer and Quinn 2000). Subsequent studies compared automated digital recorders to in-person point counts, revealing substantial variation in the performance of automated versus in-person point counts in diverse habitat types around the globe (e.g. Hutto and Stutzman 2009; Digby et al. 2013; Alquezar and Machado 2015; Leach et al. 2016; Wheeldon et al. 2019). Four recent reviews compare sound recordings versus human point counts and suggest that autonomous recorders sometimes out-perform detections by humans, and sometimes under-perform (Shonfield and Bayne 2017; Darras et al. 2018, 2019; Sugai et al. 2019). For example, in a review of 17 comparisons of automated versus in-person point counts, autonomous recorders detected higher species richness in 18% of studies, equal species richness in 47% of studies, and lower species richness in 35% of studies (Shonfield and Bayne 2017). My results showed that new small autonomous recorders produce reliable estimates of bird species richness in an insular temperate bird community in eastern Canada, although all of the autonomous recorders under-estimated species richness compared to in-person point counts. Under-estimation in recordings is well known from other studies of larger models of autonomous recorders (Hutto and Stutzman 2009; Shonfield and Bayne 2017) and my results suggest that small acoustic recorders under-estimate species richness in side-by-side comparisons of in-person versus automated recordings. Of course, two of the long-recognised advantages of passive acoustic monitoring are that autonomous recorders can be left in place over longer sampling intervals, and the recordings can later be scrutinised with more advanced analytical methods (Digby et al. 2013; Marques et al. 2013). Therefore, the limitation that I have presented here may be offset with longer sampling intervals and more advanced assessment methods. It is noteworthy that my research was conducted in a north temperate ecosystem with moderate levels of biodiversity; it will be valuable for future investigations to consider the performance of autonomous recorders in areas with different levels of biodiversity.

Several species of birds were commonly missed by all of the small autonomous recorders that I tested, even though these species were heard during in-person point counts, including Alder Flycatcher (undetected in 77% of 35 recordings compared to in-person point counts), Common Yellowthroat (undetected in 31% of 45 recordings), Canada Goose (undetected in 66% of 15 recordings), Savannah Sparrow (undetected in 60% of 15 recordings), and American Redstart (undetected in 53% of 15 recordings). No particular recorder model showed a propensity to miss these birds. Why are these species prone to being missed in the recordings? The frequency spectrum of their vocalisations cannot be the explanation, because many species were regularly detected vocalising in the same frequency range as the missed species, including Yellow Warbler (*Setophaga petechia*) which was present at all point count locations and missed in only 3% of the recordings. Instead, I suspect that the explanation is the distance between the birds and the recorders. I conducted point counts in the forested region of my study site (Figure 1), and most of the birds that were missed inhabit forest edge (Alder Flycatcher), ocean shore (Canada Goose), and grassy meadows (Common Yellowthroat, Savannah Sparrow), which are habitats found at a substantial distance from the point count locations. Recognising that many of the recorders showed lower sensitivity at distances of 100 m in the sound transmission component of this investigation, I suggest that animals far from the recording site are poorly sampled by small autonomous recorders compared to in-person point counts. Alternatively, the species that were not detected by the autonomous recorders may vocalise at lower amplitudes than the species that were detected. An additional factor for consideration is that my in-person point counts involved stereo hearing, whereas the recorded point-counts involved monaural recording, which may reduce the ability to detect animals farther from the recorder. Overall, my findings reveal that these small autonomous recorders have smaller detection radii than in-person point counts. This is a factor that should be considered when autonomous recordings are used in wildlife monitoring, and careful quantification of the effective detections radius of autonomous recorders is warranted. Yip et al. (2017) and Perez-Granados et al. (2019) provide an approach for quantifying effective detection radius, and future studies could provide correction factors that field recordists could use to adjust for recordings gathered with different models of recorders. These correction factors are likely to vary from one environment to the next. Future research could also compare the larger autonomous recorders that were common in the past to the smaller autonomous recorders investigated here, facilitating comparisons of recordings made across recording models, and future research could compare estimates of abundance in addition to estimates of species richness. Finally, future research could also explore how variation in the gain settings of each of these autonomous recorders might influence their performance in point counts and in collecting high quality recordings; throughout my investigation, I used the default gain settings on each of the recorders, which appeared to yield similar sound levels across the recorders based on my visualisation of the recordings.

Quality of recordings

Birds singing at high frequencies of the avian frequency range (Figure 4) and birds singing at low frequencies of the avian frequency range (Figure 5) were recorded by all of the small autonomous recorders that I tested. I included other species of birds and other types of avian acoustic signals, including woodpecker drumming sonations, as well as non-avian acoustic signals (vocalisations of squirrels, monkeys, and frogs) in my transmission tests (Appendix). I found that these diverse types of sounds were detectable and easy to recognise in sound spectrograms at distances up to 100 m across all of the types of small recorders that I investigated. For studies of animals that vocalise at frequencies beyond my focus here (i.e. below 250 Hz or above 12 kHz), recordists should give careful attention to the sensitivity of the recorders. My recordings suggest that sounds above 12 kHz are poorly recorded, especially as the distance to the sound source increases; this limitation was most pronounced in the Song Meter Mini, the Song Meter Micro, the Swift One, and the Marantz-with-Sennheiser recorders. It is widely recognised that higher-frequency sounds experience more rapid attenuation than lower-frequency sounds in nature (Marten and Marler 1977), and yet the autonomous recorders measured here showed variation in their recording capacity above 12 kHz.

The Song Meter Mini and the SwiftOne recorders use condenser microphones, whereas the Song Meter Micro and Audiomoth use miniature Micro-Electro Mechanical Sensor (MEMS) microphones. My comparison of synthetic sounds recorded at distances between 6.25 and 100 m revealed that the MEMS microphones of the smallest recorders performed as well as the conventional condenser microphones; at greater distances from the sound source, the miniature MEMS microphones of the Audiomoth recorders outperformed the condenser microphones in detecting higher frequency sounds (Figures 3 and 4). Additional variation in microphone sensitivity for autonomous recording units is expected as microphones age (Turgeon et al. 2017), and recordists must be conscious that differences in microphone sensitivity may vary with microphone age. Indeed, the Sennheiser microphone that I used in these transmission tests had been used in many projects over many years, and the age of this microphone may explain its lower frequency response at higher frequency ranges in the transmission test. All of the small recorders were recent purchases, used for the first time in this field test (the Song Meter Micro, the Audiomoths, and the SwiftOne), or having been used for only several weeks of field recording (the Song Meter Mini).

Audiomoth housing comparison

Without an external case around the circuitboard and battery compartment, Audiomoths are usually deployed inside a plastic bag or in a waterproof plastic case. I compared the performance of the Audiomoths using these two housing methods. For point counts, I found no statistical difference between an Audiomoth housed in a plastic bag (77% detection of species detected during in-person point counts) and an Audiomoth housed in a hard-shell plastic case (83% detection). For transmission tests, I found remarkably similar sensitivity to different frequencies with varying distance (Figure 3) and remarkably similar frequency response curves (Figure 4). Therefore, the two Audiomoth housings perform equally well. Previous analyses have indicated different recording amplitudes for different types of Audiomoth housing (Metcalf et al. 2023; note that a different type of case was used in that study) and noted that the plastic bag housing can be problematic for long recordings, due to water leakage (Hill et al. 2018). Where cost is not an issue for recordists using Audiomoths, I recommend that recordists use the hard-shell plastic case, which I have shown does not diminish the performance of the recorder, yet provides protection to the recorder during travel to and from a field deployment, and makes it easy to attach the recorder to structures in the field. Careful investigation of whether the hard-shell plastic case influences the directionality of sampling is warranted (Lapp et al. 2023).

Additional observations

During this research, I collected anecdotal observations on the size, ease-of-operation, environmental impact, and price of these autonomous recorders, which I summarise here. The most notable difference across the recorders was size. The Song Meter Micro and the Audiomoth were so small and lightweight that I could carry a large number of them in the field. The slightly larger size of the Song Meter Mini and the SwiftOne meant that fewer could be carried at a time. In spite of these size differences, all of the recorders are remarkably light compared to earlier versions of field-based autonomous recorders, including external-battery-powered recorders (e.g. Hennin et al. 2009; Swiston and Mennill 2009), and earlier versions of field-based autonomous recorders (e.g. Mennill et al. 2018; Gayk and Mennill 2020).

The second major difference in these small autonomous recorders is the user interface. The Wildlife Acoustics recorders have a phone-based app that can be operated wirelessly with a phone or tablet. The Audiomoth and SwiftOne recorders, by contrast, require a cable connection to a computer. I found that using my phone was highly convenient; I could programme recorders, check the recording levels, and confirm that the recordings were being collected in the field. The Audiomoth and SwiftOne recorders feature an external light which flashes when a recording is in progress; I appreciated that the external lights allowed me to quickly confirm that the device was operating. In terms of ease-of-use, I found all types of recorders were equivalent. There was an initial learning period, but in all cases, I mastered the software and ran test recordings in less than one hour. A research assistant unfamiliar with autonomous recorders was similarly able to master launching the devices with less than an hour of effort in each case. The file naming schemes of all of the recorders was customisable and effective for easily determining when a recording was collected, and all of the devices were similar in this regard.

In terms of environmental impact, the Wildlife Acoustics recorders and Audiomoth recorders are made of hard weatherproof plastic and small circuitboards, whereas the SwiftOne recorder is made primarily of metal and features a larger circuitboard. The Wildlife Acoustics recorders shipped in all-cardboard containers, with zero plastic packaging; Audiomoth and SwiftOne recorders shipped with plastic packaging and single-use plastic wrappers and containers. All of the recorders worked well with rechargeable batteries. Note that the SwiftOne recorder includes a non-rechargeable BR1225 coin battery for the clock.

There is significant variation in price of these small autonomous recorders. Audiomoths cost $80 ($35 more for a hard-shall case); Song Meter Micros cost $249 USD; SwiftOnes cost $349 USD; and Song Meter Minis cost $499 USD (prices as of January 2024). (Note: Open Acoustics uses a collective buying service and recorders are available only when a purchasing campaign is active.) The costs of batteries and storage media should be similar across the devices, although the Audiomoth and Song Meter Micro require one fewer AA battery, and the SwiftOne requires the higher cost of D-cell batteries. On top of the price, diverse factors may steer recordists towards different models of recorder, including variation in customer support from the manufacturers, availability of the recorders for purchase, ease-of-use for field-based programming of the recorders, interest in supporting open-source products, and continuity with pre-existing recording protocols.

Conclusion

In a field-based setting, I studied four widely used small autonomous recorders for bioacoustic research, comparing their performance in avian point counts and assessing the quality of the recordings. All of the small autonomous recorders that I tested performed comparably well to each other in point counts, with the Wildlife Acoustics

Song Meter Mini showing the highest proportion of species detected during in-person point counts, and the Cornell Swift One and Audiomoth-in-a-plastic-bag showing lower proportions. All of the recorders under-estimated species richness relative to in-person point counts, missing 12 to 24% of species detected during in-person point counts. I suggest that bird species missed during point counts using the autonomous recordings were those far from the microphones. The recorders varied in their sensitivity to higher frequencies, where some recorders were not well-suited to recording frequencies above 12 kHz at greater distances. At frequencies less than 12 kHz, which is a typical frequency range for most birds and many mammals, the recorders performed similarly well, with only subtle differences in frequency response between the devices. I conclude that all of these autonomous recorders are useful tools in the context of avian point counts and in bioacoustic field studies.

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Disclosure statement

I purchased all of the recorders at full price using my research grant. None of the manufacturers of the recorders were aware that I was purchasing the recorders to be part of this comparison. As an active researcher in the field of bioacoustics, I have relationships with two of the manufacturers. In 2004-2005, I conducted postdoctoral research at the Cornell Lab of Ornithology, which produces the SwiftOne recorder. Since 2022, Wildlife Acoustics has collaborated with my lab on a Mitacs Accelerate project studying nocturnal flight calls of migratory birds, led by a postdoctoral researcher in my lab. In both cases, I feel that my affiliation with the Cornell Lab of Ornithology and Wildlife Acoustics does not compromise my ability to objectively evaluate the recordings. In particular, my analyses were conducted with the type of recorder anonymized.

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Appendix

I assembled a playback stimulus to compare recordings from different autonomous recorders, including both synthetic tones and animal sounds from diverse birds, frogs, and mammals, using recordings from my laboratory's sound archive. The animals included in the recording, in order of presentation, were: White-throated Sparrow (*Zonotrichia albicollis*), Eastern Phoebe (*Sayornis phoebe*), Tree Swallow (*Tachycineta bicolor*), Chipping Sparrow (*Spizella passerina*), Rufous-and-white Wren (*Thryophilus rufalbus*), Rufous-naped Wren (*Campylorhynchus rufinucha*), House Wren (*Troglodytes troglodytes*), Long-tailed Manakin (*Chiroxiphia linearis*), Royal Flycatcher (*Onychorhynchus coronatus*), White-eared Ground-sparrow (*Melozone leucotis*), drumming sonations from Pale-billed Woodpecker (*Campephilus guatemalensis*) and Pileated Woodpecker (*Dryocopus pileatus*), and calls of Eastern Red Squirrel (*Tamiasciurus hudsonicus*), Richardson's Ground Squirrel (*Urocitellus richardsonii*), Spider Monkey (*Ateles geoffroyi*), Grey Treefrog (*Dryophytes versicolor*), Spring Peeper (*Pseudacris crucifer*), and Neotropical Yellow Toad (*Incilius luetkenii*). The stimulus set was interspersed with loud pure tones and frequency modulated tones which served as "landmarks" for detecting the animal sounds in the recordings. The stimulus set concluded with a 30-second frequency sweep as described in the main text, and a series of 0.5-second tones starting at 20 kHz and descending to 1 kHz as described in the main text. The stimulus set was 1 min 31 seconds in length. The stimulus is included as an appendix (supplementary material 1), as well as the field recordings of this stimulus from the autonomous recorders and a non-autonomous recorder as described in the main text (supplementary materials 2-7). Each of the field recordings includes three repeats of the stimulus with a distance-of-separation of 6.25 m, 12.5 m, 25 m, 50 m, and 100 m between the loudspeaker and the autonomous recorders.