Scientific Experiments

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Passive Acoustic Monitoring

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The Repertoire of a Wood Thrush in My Home 'Patch'

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New York State, USA

Listen to a Wood Thrush singing on YouTube: https://youtu.be/fygGypTSvqw

The melodious song of a Wood Thrush echoing through the woods in the northeastern United States is both sweet and haunting. These birds arrive here in early May after wintering in Central America and Mexico. Only the **male** is known to sing after arrival, and during the breeding season which ends in early to mid-July. It is usually difficult to locate a Wood Thrush in a dense forest, but he lets you know he is there by singing away.

It was sheer delight to hear a Wood Thrush in the woods behind my house for a few days two years in a row. I wanted to know more about this elusive bird through his voice, the only way I knew of his presence.

Was it the same individual in my woods in 2021 and 2022? Will he return next spring?

Our team analyzed the Wood Thrush songs I had recorded at sunrise and sunset in 2022 over a two-week period. From these we learned his musical lure and unique vocalization patterns, different from those of the Wood Thrush in 2021 and three other Wood Thrushes in the northeatern USA. Now we may well be able to identify this bird if he safely journeys back to my 'patch' next spring, without using bands or other visual markers.

Below is a description of our findings.

Wood Thrush vocalization dates and times

On the 15th of May 2021, when I returned after a birding field trip with a friend, we heard the '*ee-oh-lay*' song of a Wood Thrush coming from the woods behind my house. We stopped on the driveway and listened. Yes, it was a Wood Thrush, we both knew the characteristic '*ee-oh-lay'* song, typically heard in large wooded areas around here. It was the first time in twenty-three years that there was a Wood Thrush in my own Home 'patch'!

David, who was visiting from Massachusetts, and I searched the woods to find this elusive bird. He was singing away, the sound reverberating through the trees, but it took over an hour to locate him. He was perched on a dead branch and continued to sing - unperturbed by us or our cameras. We snapped a few photos and David recorded a video of the bird as he sang.

I heard the eerie songs of this Wood Thrush off and on for the next twelve days, and then he was silent.

A year later, on May 17, 2022, I heard a Wood Thrush, his loud and clear melodies coming into my living room. He must have been at the edge of the woods in my backyard, about fifty feet away, but hidden from view in the dense foliage. Then from June 2 to June 20, he sang several times each day. Sometimes he was close and sometimes the sound came from deeper in the woods, but always loud enough to be heard inside my home. A few times, early in the morning, he gave loud, agitated staccato '*pit pit*' calls, and then resumed to melodious singing.

I started recording his lilting voice at sunrise and at sunset from June 8 onwards and noted the singing times during the day when I was at home and not distracted by other noise. His singing became less frequent and for shorter durations from June 21 to June 23. I did not hear him at all on June 24, briefly on June 25 and for the last time on June 27, just before sunset.

From the collection of twenty-one audio recordings of about one minute each, we now have a ‘fingerprint’ of this bird’s repertoire. We also recorded three other Wood Thrush songs in New York and Massachusetts. Each bird had a unique signature representing his identity.

Details of our findings are described here. We are preparing for next year and hope to enhance our learning of the Wood Thrush species then with better instrumentation and more rigorous observations.

The presence of a Wood Thrush established from his singing in the spring of 2021 and 2022 is shown in Fig. 1. He vocalized at sunrise and at sunset, repeating short phrases or songs for fifteen to thirty minutes and for shorter durations of two to five minutes during the day. Singing during the day was more pronounced between June 10 and June 20 (Fig. 2). The clock time for vocalization on June 12 as well as the local sunrise and sunset timings are shown in Fig. 3. He started twenty-four minutes before sunrise, and his last bout began about twenty minutes before sunset. During the day, he vocalized more often in the morning and evening hours.

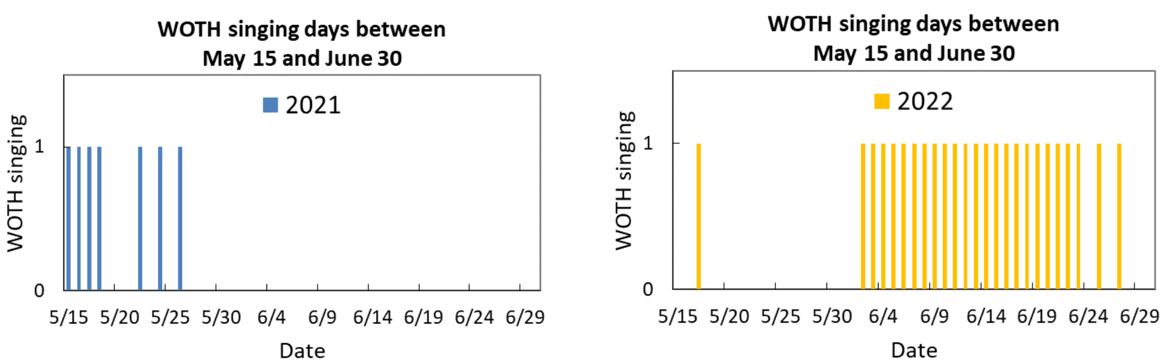


Fig. 1. Wood Thrush singing dates (represented by vertical bars) between May 15 and June 30 in 2021 and 2022.

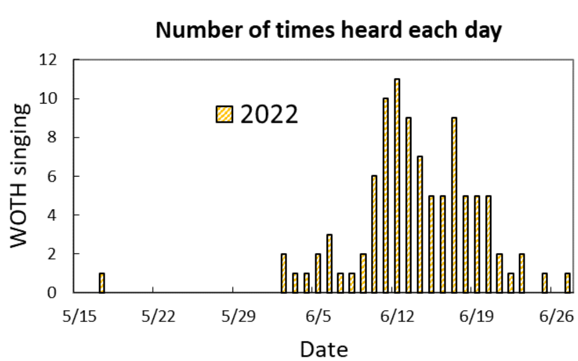


Fig. 2. Number of times I heard the Wood Thrush each day.

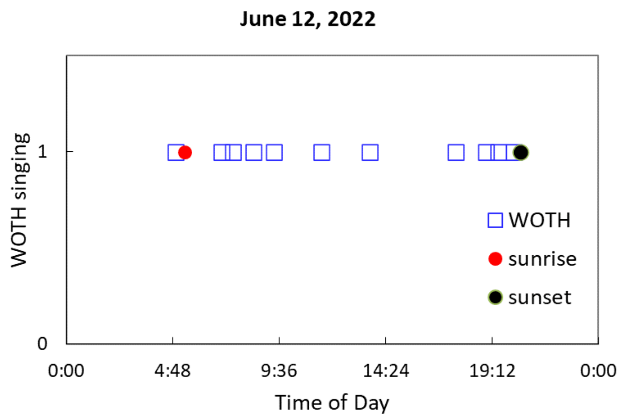


Fig. 3. Vocalization times as recorded on June 12 and the local sunrise and sunset timings.

Audio Recordings and Analysis

Listen to a recording on YouTube: https://youtu.be/fygGypTSvqw

We used the Merlin App on an iPhone and a small shotgun microphone with wind filter (either Movo PR-2-PM or Saramonic) to record the songs. The audio files in '.wav' format for this bird, named ***WOTH-2***, were analyzed using Raven Pro software from Cornell University. The procedure for noise reduction and some sources of error are listed in Appendix A.

Fig. 4 shows the oscillogram and spectrogram of a forty-nine second recording of *WOTH-2* on June 14, 2022. It has 13 songs, each lasting 1.2 to 1.5 seconds with a gap of ~ 2.5 seconds between songs.

Looking at the spectrogram of an individual song more closely in Fig. 5, there are three elements of each song, *p1*, *p2* and *p3*. The first part '*p1*' is a low frequency, low volume '*bup*' sound, repeated two or three times. The second part '*p2*' is the characteristic '*ee-oh-lay*' with which most birders associate the Wood Thrush. The third part '*p3*' is a trill in a higher frequency range. In all recordings '*p2*' is present, but '*p1*' and '*p3*' may be absent. Both '*p1*' and '*p3*' are difficult to hear because of lower sound volumes and high frequency attenuation of '*p3*' when the bird is further away in the woods.

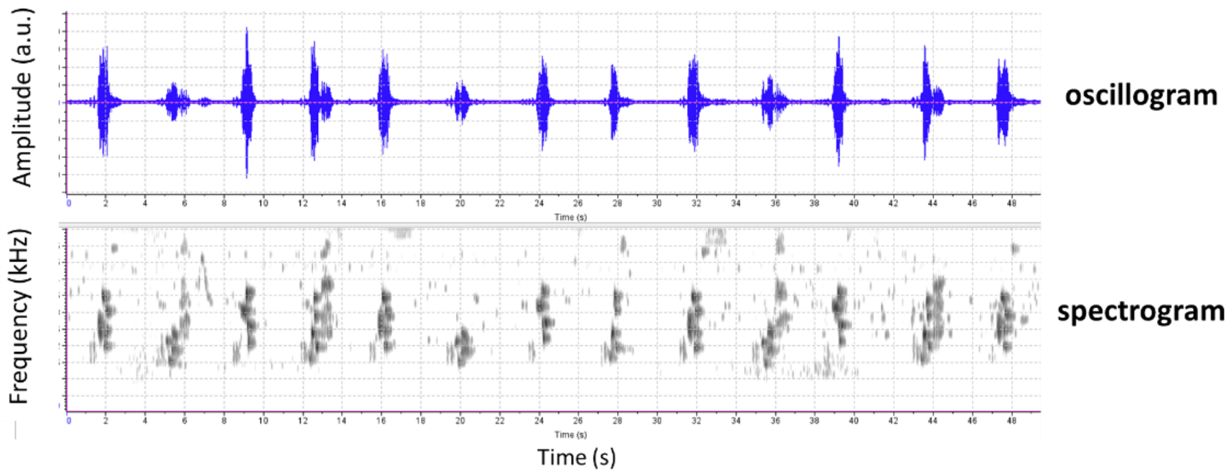


Fig. 4. Oscillogram (microphone pressure/amplitude vs. time) and spectrogram (frequency vs. time) of an audio recording on June 14, 2022. This recording contains thirteen individual songs.

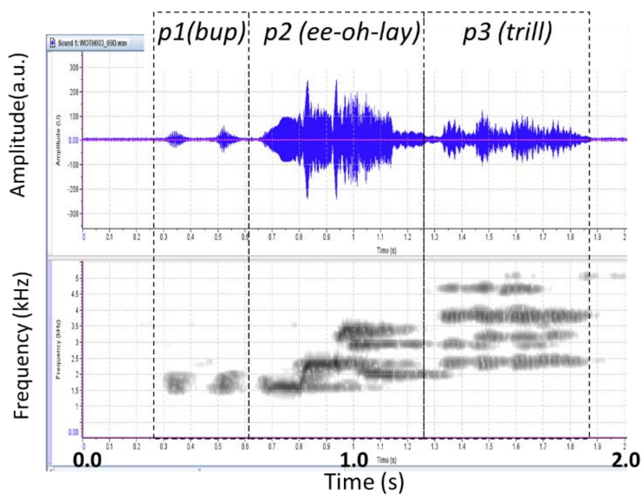


Fig. 5. The *p1*, *p2* and *p3* elements of the Wood Thrush song.

We characterized each song by its '*p2*' element. There are four variations of this element, labeled A, B, C and D. The designation is arbitrary, but as discussed later, we labeled these in the preferred sequence used by the bird. The spectrograms of these variations are shown in Fig. 6. Each element comprises four or five frequency bands with different starting and ending times. Although the general '*ee-oh-lay*' pattern is maintained, these variations are clearly distinguishable when listening carefully or from the spectrograms of the audio recordings.

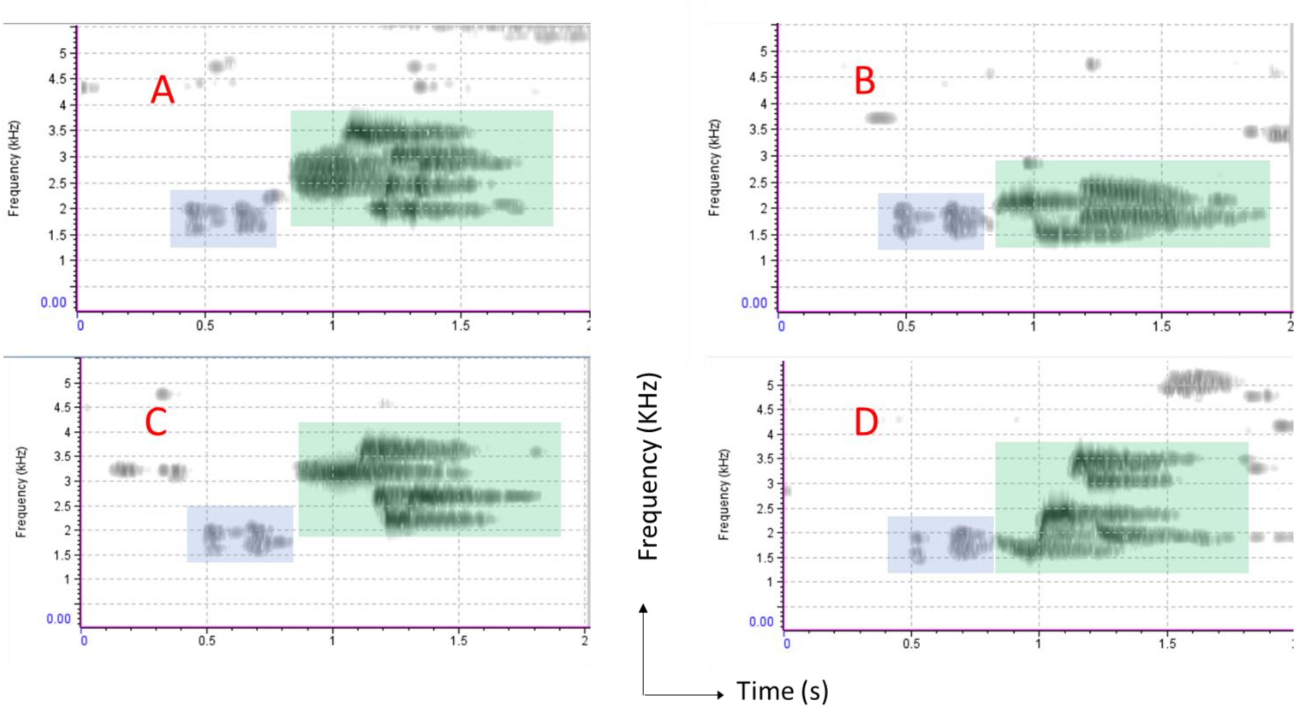


Fig. 6. Spectrograms of the four variations of '*p2*' element shaded green rectangles.

Further examination of the spectrograms revealed small variations in the frequencies and timings within each of the four '*p2*' elements produced at different times within the same recording and in recordings made on different days or different times of the day. To quantify how well the song types are repeated, we utilized Raven Pro software from Cornell University.

A rectangular box was drawn by hand around each of the frequency bands in the spectrogram as shown in Fig. 7, with the left side of the box close to the start time. The following two parameters were calculated for each band:

1. Center Frequency: The frequency that divides the selection into two frequency intervals of equal energy.
2. Relative Start Time: start time of each band with respect to the earliest start time.

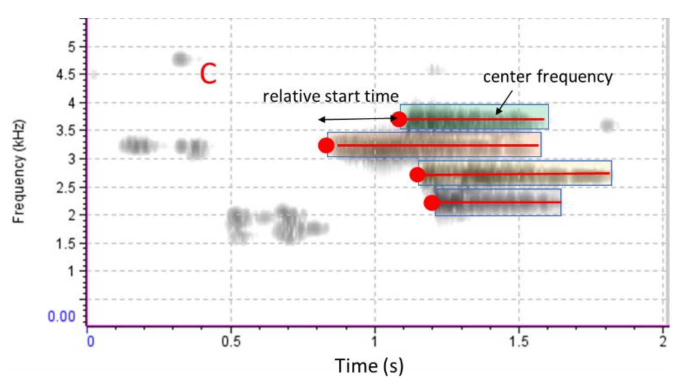


Fig. 7. Rectangular boxes covering each of the four frequency bands in song C.

In Fig. 8, the center frequency is plotted against relative start time for each song type in an audio recording shown in Fig. 4. There are small variations for each song type, but the overall pattern is preserved.

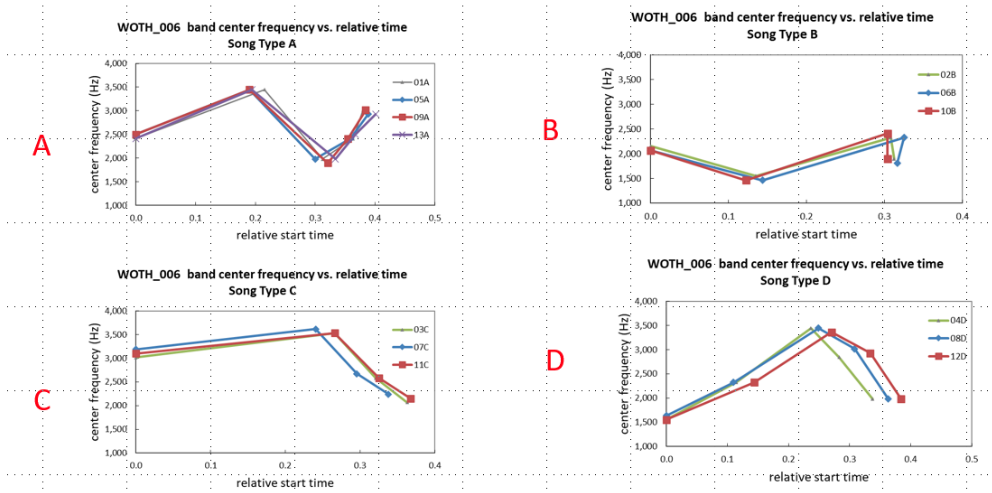


Fig. 8. Center frequency vs. relative start time for the four song types of *WOTH-2*.

The sequence in which the bird sang different songs was typically A, B, C and D but sometimes one of the song types was missing or the order was changed. In all the recordings with a total of 235 songs, we did not find any case where a song type was immediately followed by the same song type. Fig. 9 shows a matrix with % values of one song type followed by another song type. For example, song A was never followed by song A, 67% of the time it was followed by song B, 15% of the time by song C and 18% of the time by song D. Similarly, 19% of the time song C was followed by song A, 16% of the time by song B, 67% of the time by song D and never by song C. This non-repetitive pattern adds to the musical charm of his song (Appendix B.)

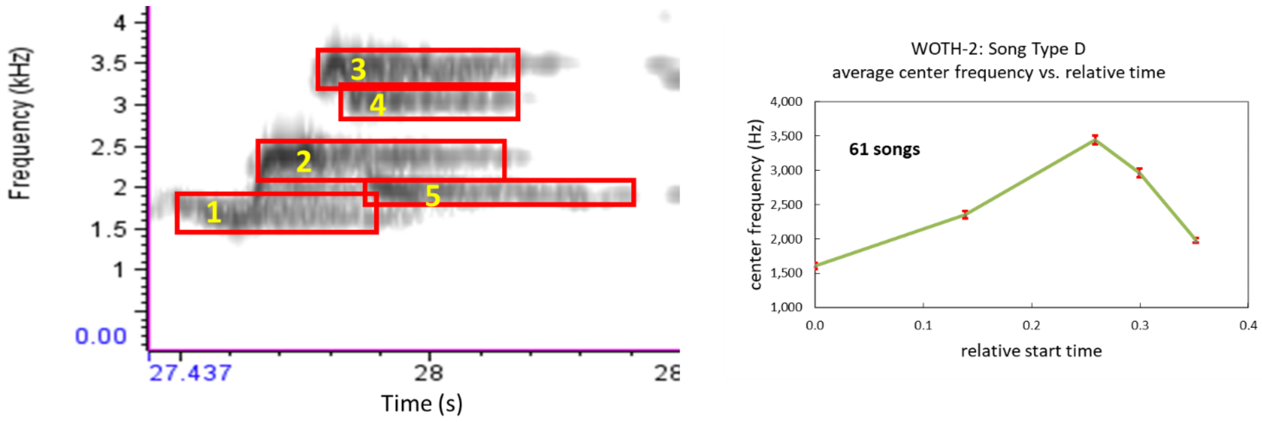
	A	B	C	D
A	0	67%	15%	18%
B	14%	0	68%	19%
C	19%	16%	0	65%
D	56%	26%	19%	0

number of songs = 235

Fig. 9. A 2 x 2 matrix showing how often a song type was followed by same or another song type

How well does a Wood Thrush reproduce a song

We examined sixty-one song D recordings of the *WOTH-2* obtained between June 8 and June 21, 2022. For each recording, we measured the center frequency and relative start time of the five bands in the song as shown in Fig. 10 (a). In Fig. 10 (b) the average center frequency of sixty-one songs is plotted against average relative start time. Red error bars indicate the standard deviation of center frequency which is ≤ 2.7%.

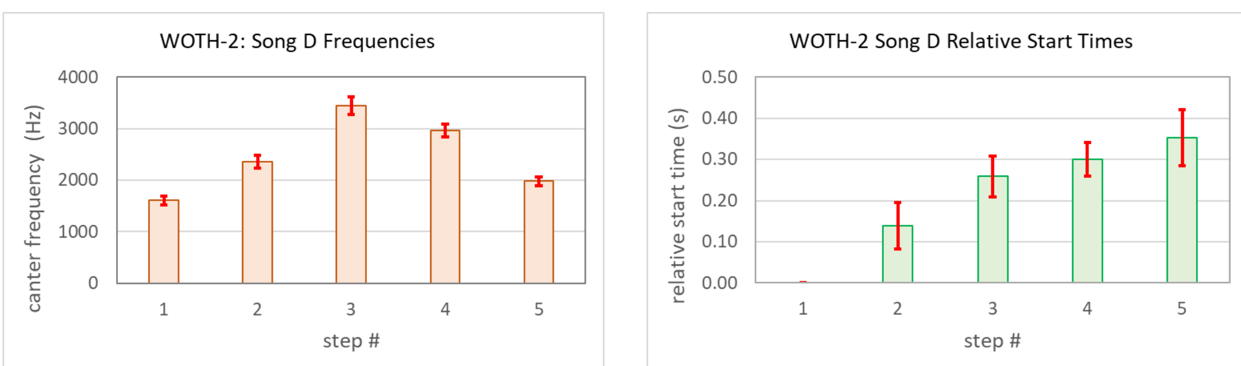


(a) (b)

Fig. 10. (a) Spectrogram of song D showing five rectangles for measuring center frequency and relative start time, (b) average center frequency vs. average relative start time of sixty-one song D recordings. Red error bars show standard deviation of center frequency

The start time of each band is the time corresponding to the left-side of the rectangle. The rectangle is hand drawn, and may result in a small error in the start time.

Fig. 11 shows the (a) average center frequency and (b) average relative start times with red error bars indicate maximum variation range, (maximum - minimum) value in sixty-one songs.



(a) (b)

Fig. 11. Bar charts of (a) center frequency and (b) relative start time of bands 1 to 5 for song D. Red error bars show (maximum – minimum) range.

Other Wood Thrush Songs

In early July when the *WOTH-2* in my home 'patch' became silent, we went in search of other Wood Thrushes. Our team member Mark recorded two birds in Hadley, Massachusetts (at Mitches Marina on the Connecticut river and Mt. Holyoke), about 100 miles from my home 'patch'. A third recording was made about twenty miles from my home 'patch' in Millbrook, New York. By mid-July we did not find any singing Wood Thrushes in our limited search in areas where these birds were singing regularly in May and June.

Each of the three birds also had four distinct songs, somewhat different from our resident bird. The spectrograms of their songs are shown in Figs. 12, 13 and 14, with '*p2*' elements highlighted by shaded green areas. Both Mt. Holyoke and Millbrook Wood Thrush recordings contained '*p1*' elements, and '*p3*' element were present only in the Millbrook recording. The Millbrook bird was very close, perhaps 30 feet or less away, but we were not able to locate him. His voice was the loudest, and details of the '*p3*' element are visible in the spectrogram – although sometimes it overlapped with the '*p2*' element.

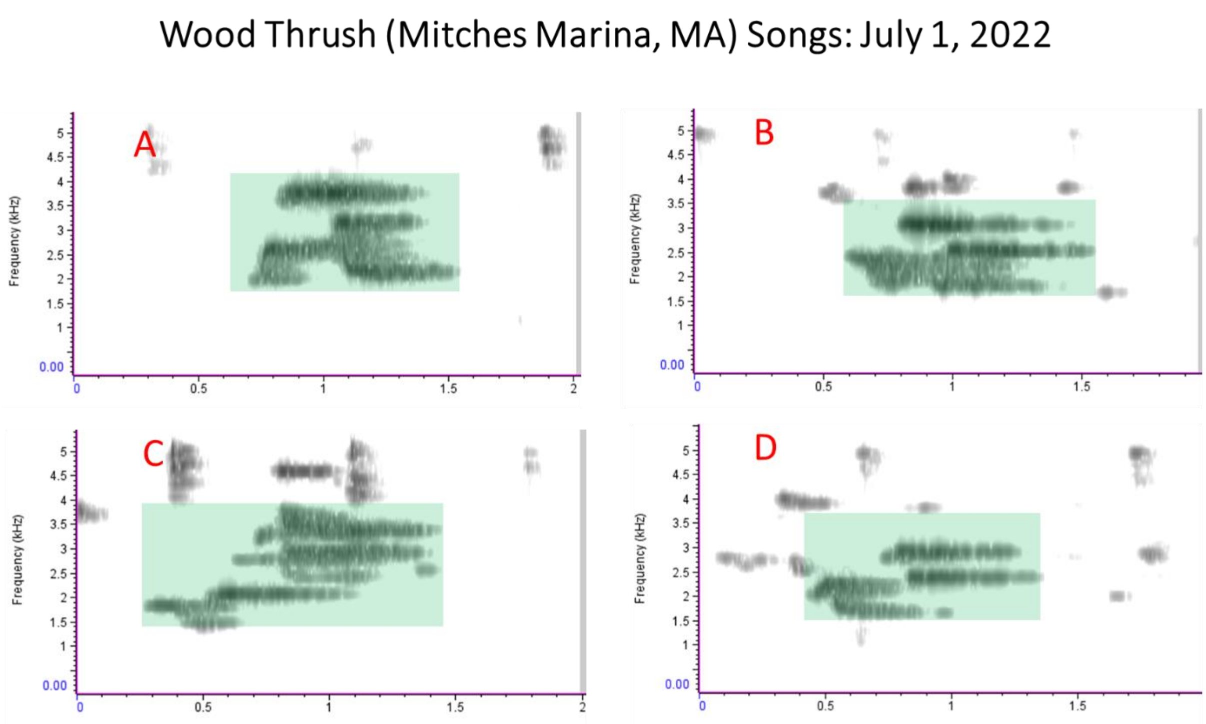


Fig. 12. Spectrograms of the four songs of the Wood Thrush at Mitches Marina, Hadley, Massachusetts.

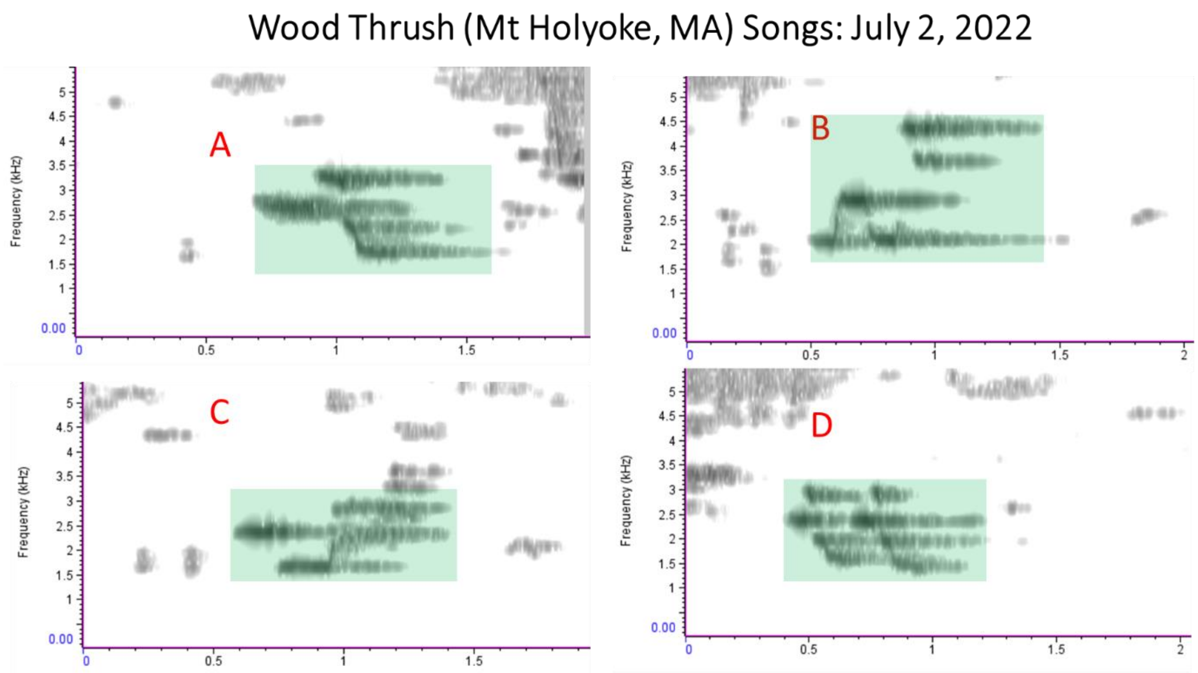


Fig. 13. Spectrograms of the four songs of the Wood Thrush on Mt. Holyoke, Hadley, Massachusetts.

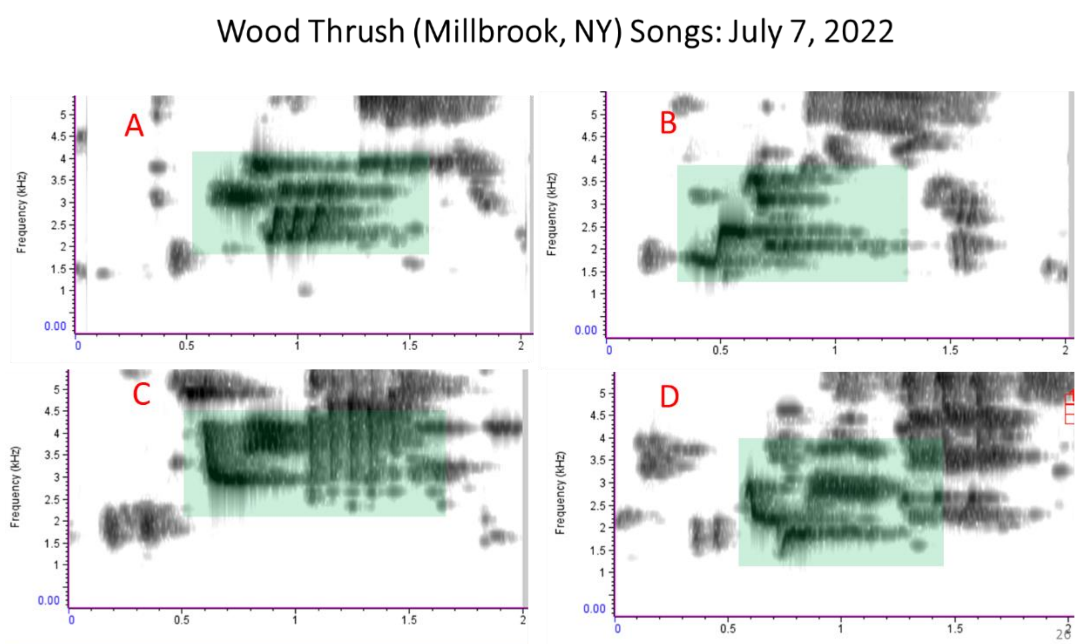


Fig. 14. Spectrograms of the four songs of the Wood Thrush in Millbrook, NY.

Comparing Different Wood Thrushes

The '*p1*' elements of *WOTH-2*, *Mt. Holyoke* and *Millbrook WOTHs* when detected were similar – with '*bup*' calls made in the 1.2 kHz to 1.5 kHz frequency range and a period between 0.15 s and 0.18 s.

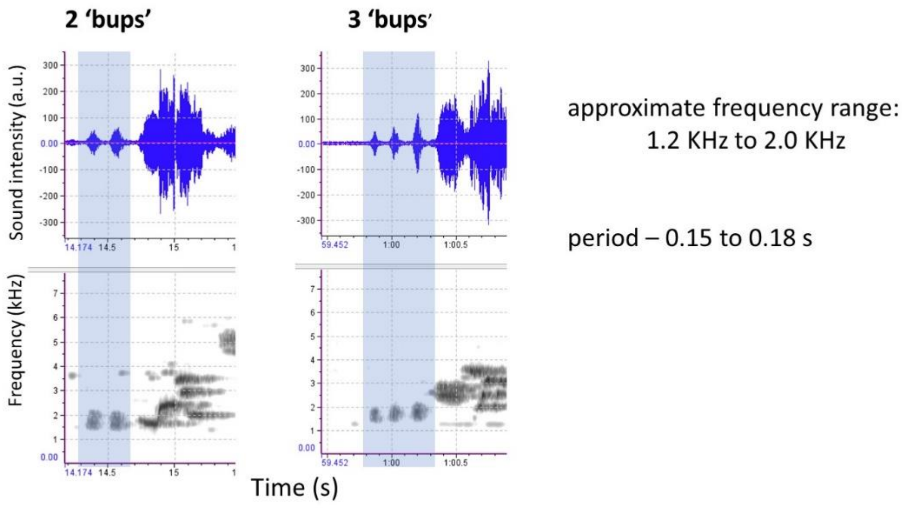


Fig. 15. Oscillogram and spectrograms of the *WOTH-2* with '*p1*' elements highlighted

Most of the '*p2*' elements of the Wood Thrushes were different but we found two matching cases. Song A of *WOTH-2* was similar to song B of the *Mitches Marina WOTH*.

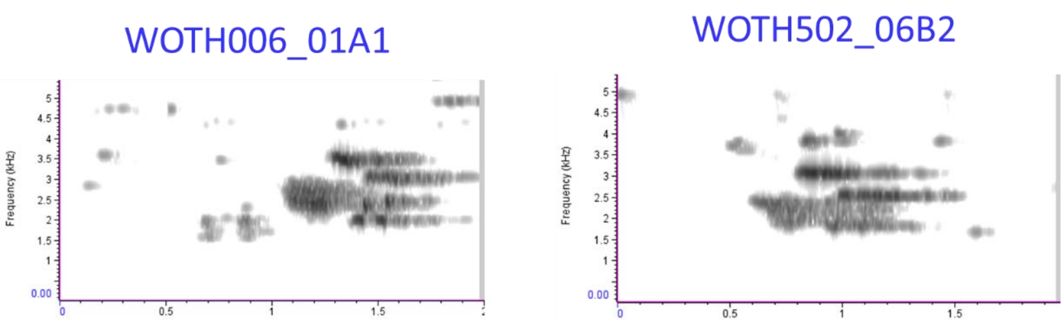


Fig. 16. Spectrograms of *WOTH-2* (WOTH006) song A and song B of the Wood Thrush (WOTH502) singing in Mitches Marina.

Song D of the *WOTH-2* matched song B of the *Millbrook WOTH*. We compared the center frequencies and relative start times of *WOTH-2* and *Millbrook WOTH* (Fig. 18). These parameters for the *Millbrook WOTH* are within the variations observed in the *WOTH-2* song (Fig. 10b). These two birds share one song but not the other three.

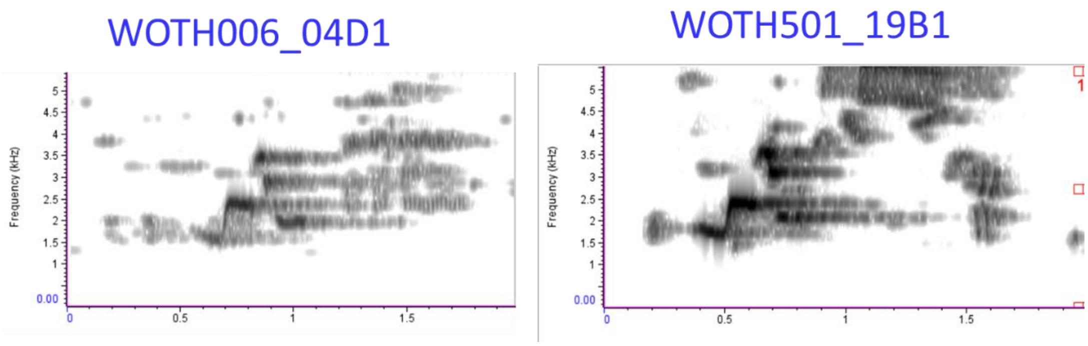


Fig. 17. Spectrograms of *WOTH-2* (WOTH006) song D and *Millbrook WOTH* (WOTH501) song B.

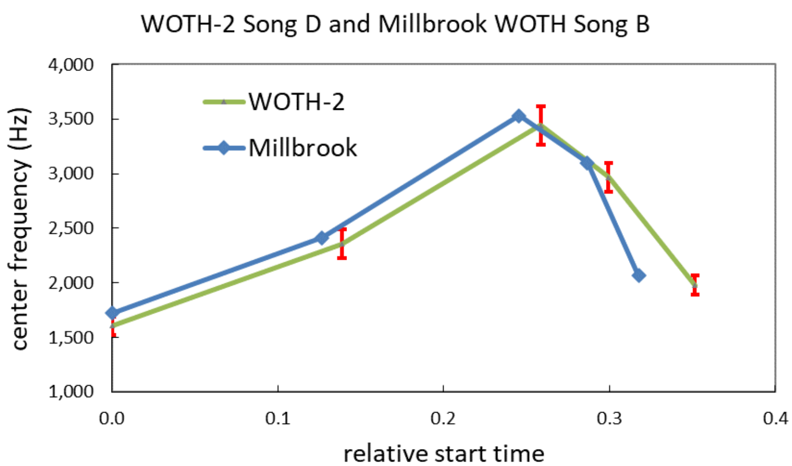


Fig. 18. Center frequency vs. relative start time of the average of sixty-one *WOTH-2* song D's and one song B of the *Millbrook WOTH*. Red error bars indicate the total variation (maximum – minimum) in *WOTH-2* songs.

We did not attempt to compare '*p3*' elements of these songs because of the poor recording quality of this element, often overlapping with the tail-end of '*p2*'. Only if all the '*p2*' elements in two birds match will we attempt to confirm the identity of an individual bird by comparing '*p3*' elements as well.

WOTH-1 Wood Thrush Songs

Listen to this Wood Thrush singing on YouTube: https://youtu.be/DGCTc169DvU

Listening to David's video and viewing the spectrograms of the Wood Thrush in 2021, *named WOTH-1*, we discerned that this was a different individual. The twenty-eight second video captured four song types, labeled A, B, C, D in Fig. 19. The spectrograms of these four song types are shown in Fig. 20.

We compared the '*p2*' elements of the *WOTH-1* songs with the other four Wood Thrush songs reported earlier. His songs A, B and D are unique. There is a reasonably good match of his song type C with the *Millbrook WOTH* song type C (Fig. 21).

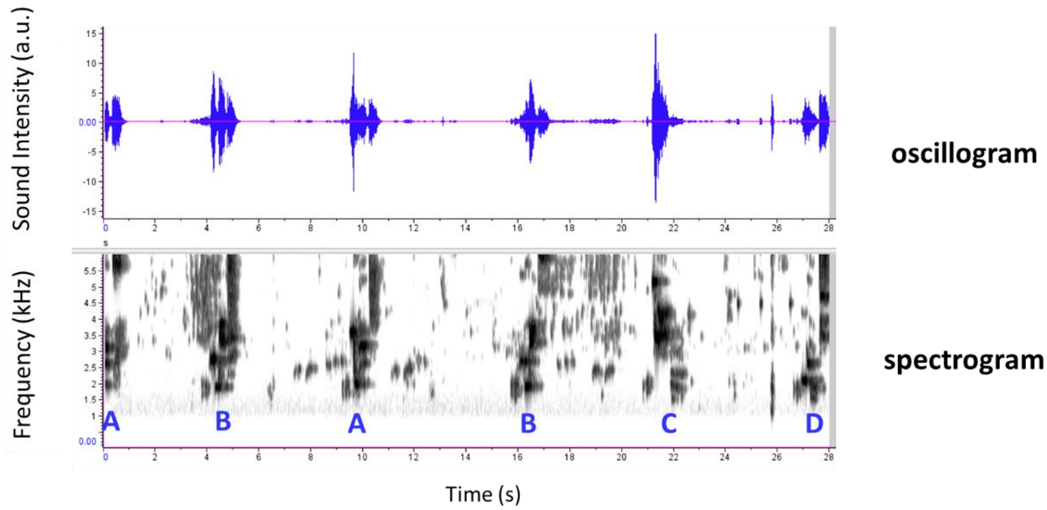


Fig. 19. Oscillogram and spectrogram of the video recording of *WOTH-1* on May 16, 2021.

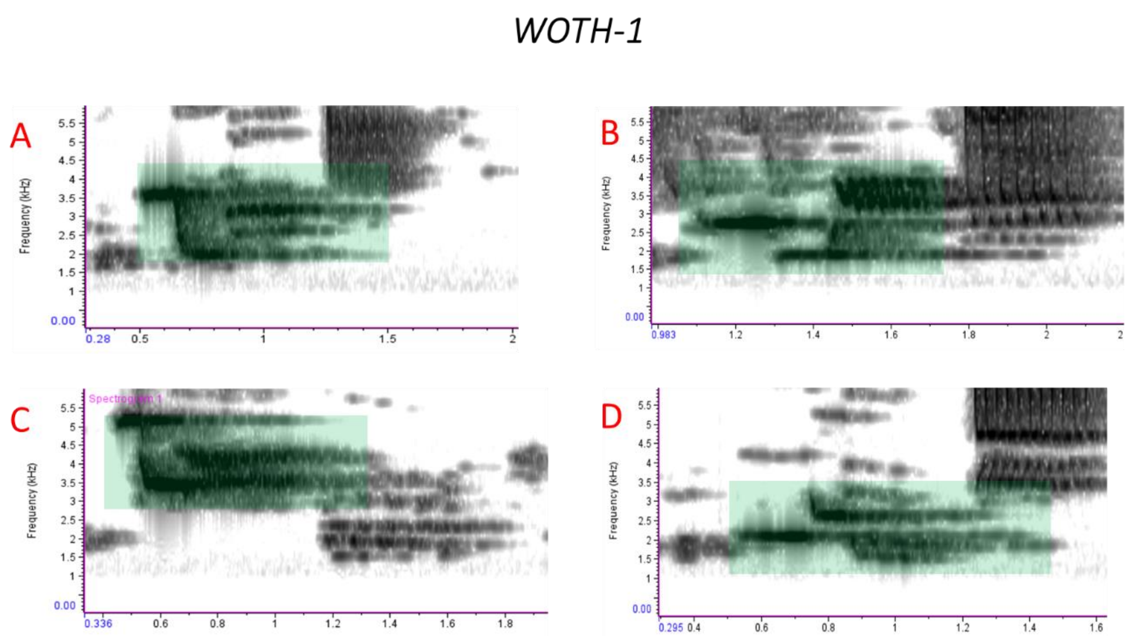


Fig. 20. Spectrograms of *WOTH-1* songs A, B, C and D with *'p2'* elements shaded in green.

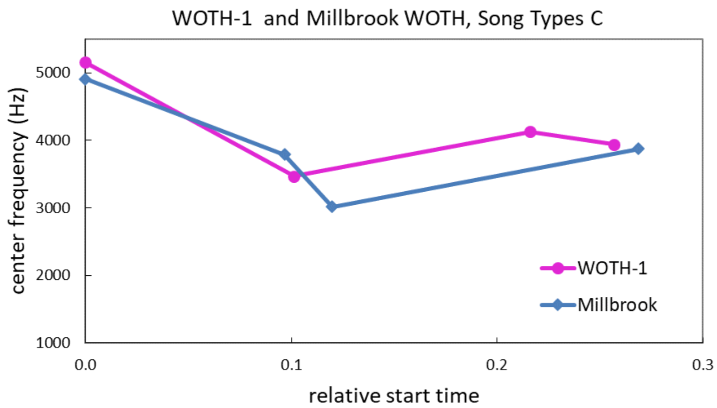


Fig. 21. Center frequency vs. relative start time of *WOTH* -1and *MillBrook WOTH* song types C.

The ‘*p1*’ element in this *WOTH-1* songs had a slightly different signature than *WOTH-2, Mt Holyoke and Millbrook WOTHs* in that its frequency range was higher – 1.5 kHz to 2.0 kHz compared with 1.2 kHz to 1.5 kHz for the other three Wood Thrushes.

Common Features in Northeastern Wood Thrush Songs

All five Wood Thrush songs recorded by us exhibited distinct but temporal overlapping tones in the ‘*p2*’ elements. The differences in this part of the songs came from the tone frequencies, relative start times and the duration of each tone. The range of center frequencies of ‘*p2*’ elements of each Wood Thrush are listed in Table 1.

Further investigation of these tones and their relationship to music keys is discussed in Appendix B.

Wood Thrush Name	Maximum Center Frequency (Hz)	Minimum Center frequency (Hz)
WOTH-1	5156	1594
WOTH-2	3617	1464
Mitche’s Marina WOTH	3704	1722
1464Mt Holyoke WOTH	4306	1464
Millbrook WOTH	4909	1722

Appendix A

Noise Reduction and Sources of Error

Audio recordings were made with the Merlin App on an iPhone with a sampling rate of 44.1 kHz. In the spectrogram analysis, the minimum hop frequency (frequency step) is 86.133 Hz, and the corresponding minimum time step is 0.0058 seconds. Note that the error bars shown in Fig. 18 indicating total variation in center frequency are only 2 - 4X the minimum frequency step.

We attempted to remove background noise and other signals from the Wood Thrush audio recordings as much as possible without deteriorating the signals of interest. The cleanup process steps are listed below:

1. A band filter (1 Hz to 10 kHz) was applied in **Raven** software to eliminate low and high frequency noise.
2. Background noise reduction was carried out using **Audacity** software. After loading the filtered file, the Y-axis scale was changed to dB. A representative area with no Wood Thrush signal was selected to get the noise profile. Noise reduction in other areas was applied twice using the parameters in the screen shot in Fig. A1.
3. In some recordings background noise varied over the recording time. In such cases, noise reduction was carried out separately for different areas using noise profile from each area.

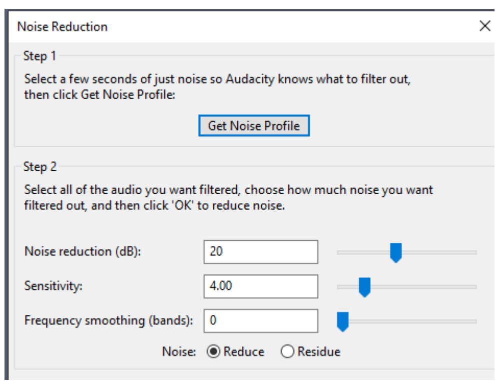


Fig. A1. Screen shot of noise reduction GUI in Audacity software.

Sources of Error in Song Analysis

Errors that may be introduced due to overlapping signals from sources external to the Wood Thrush vocalization, noise reduction procedure in Audacity and minimum frequency resolution in Raven are mentioned above. These may have a small impact on the estimated center frequency in each of the frequency bands in the '*p2*' element of the song. Three additional sources of error are mentioned below:

1. Relative start time is dependent on the location of the rectangular box hand drawn by the user and may introduce an error of ≤ 0.02 s. Alternatively, the hand drawn box area may be isolated using a frequency band filter and the start time determined more accurately from the oscillogram. However, this procedure is more time consuming.

2. Overlapping '*p2*' and '*p3*' elements in some of the song recordings affect the center frequency of the '*p2*' element. To minimize this error in comparing unique '*p2*' elements of each bird, we attempted to select recordings in which no significant '*p3*' elements were present whenever possible
3. High frequency signal attenuation varied with the location and surroundings of the Wood Thrush and may introduce a shift in center frequency.

Based on our analysis of Wood Thrush audio records, we are fairly confident that this process will identify a Wood Thrush by the '*p2*' element of his song. We will have a chance to verify this claim next year by recording songs from a larger number of birds in the northeastern USA.

Appendix B

Musical Lure of Wood Thrush

The '*p2*' element of the Wood Thrush song heard in the northeastern USA has a musical quality very pleasing to the human ear. We see pure tones in spectrograms of these songs. It is interesting to note that the frequencies used by the Wood Thrushes fall on the music keys in the 6th and 7th octaves. The lowest frequency in the Wood Thrush song corresponds to the F sharp (F#) key in the 6th octave.

Music key frequencies in the chromatic scale follow the rule that starting with the lowest frequency f_0, the frequencies of the subsequent higher keys are calculated as

$$f_N = \ f_0 \times 2^{\frac{N}{12}}$$

where N = 1, 2 3….

Music key frequencies starting with F#6 key (1479 Hz) set = 0 are plotted in Fig. B1. The *WOTH-2* '*p2*' song frequencies shown in red dots are overlayed on the music key frequency differences. There is a strong similarity between the steps in the music keys and the steps in the pure tones of the Wood Thrush songs.

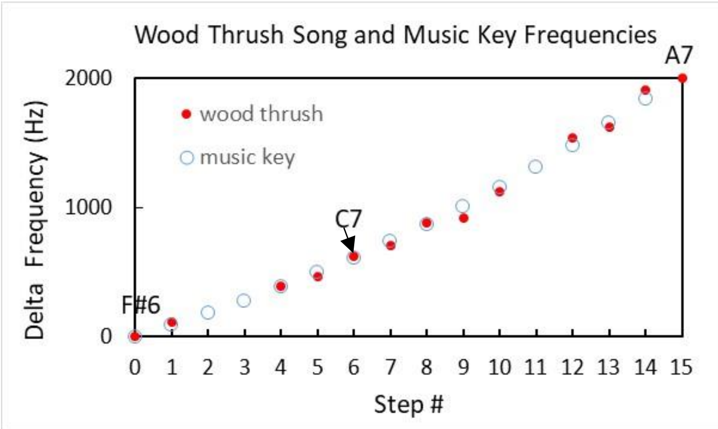


Fig. B1. Music key and *WOTH-2* '*p2*' song frequencies above F#6 key frequency.

Another feature of the Wood Thrush is that each song type is followed by a different song type (Fig. 9.) In 'Birdsong for the Curious Naturalist', Donald Kroodsma points out that some of the magic of the Wood Thrush is lost if the same song is repeated. He demonstrates this by artificially generating such recordings. See link

http://www.birdsongforthecurious.com/recording.php?page=133

for recordings ♫439 and ♫443 and compare with the original singing routine. Music appreciation is subjective, but most listeners would agree with this assertion.

Table B1 lists the center frequencies of each *WOTH-2* song, the relative start time of the tone and the corresponding music key. The Wood Thrush is singing in the keys similar to F#6, G#,6, A#6, B6, C7, D7, D#7, E7, F#7, G7, G#7 and A7.

Table B1. *WOTH-2* '*p2*' song center frequencies, relative start times and corresponding music keys.

Song A	Center Frequency (Hz)	start time (s)	Music Key	Key Frequency (Hz)
	2455	0.00	D#7	2489
	3445	0.20	A7	3322
	1960	0.32	B6	1975
	2433	0.36	D#7	2489
	2972	0.39	F#7	2959

Song B	Center Frequency (Hz)	start time (s)	Music Key	Key Frequency (Hz)
	2096	0.00	C7	2093
	1493	0.26	F#6	1479
	2354	0.31	D7	2349
	1866	0.36	A#6	1864

Song C	Center Frequency (Hz)	start time (s)	Music Key	Key Frequency (Hz)
	3101	0.00	G7	3135
	3560	0.26	A7	3520
	2613	0.31	E7	2637
	2153	0.36	C7	2093

Song D	Center Frequency (Hz)	start time (s)	Music Key	Key Frequency (Hz)
	1607	0.00	G6	1567
	2357	0.14	D7	2357
	3440	0.26	G#7	3322
	2966	0.30	F#7	2966
	1979	0.35	B6	1975

Hermit Thrush, another bird in the same *Turdidae* family as the Wood Thrush, has a similar musical quality in its songs. A study of Hermit Thrush songs by Doolittle et. al. (https://www.pnas.org/doi/abs/10.1073/pnas.1406023111) found that the frequencies selected by the birds were overtones of a fundamental frequency. Although there is sufficient evidence to support the overtone hypothesis, there is no physiological explanation of how such pitches are produced.

In our limited dataset, we found stronger evidence of the Wood Thrush preference to music keys in the chromatic scale than to overtones. This is illustrated in Fig. B2 which includes corresponding overtone frequencies overlayed in the plot in Fig. B1. The fundamental frequency of the overtones is set to 140 Hz to match the frequency steps in the Wood Thrush songs. Hence, these overtones are in the range of 10X to 25X of the fundamental. As in the case of a Hermit Thrush, the physiological basis of these frequencies is not apparent.

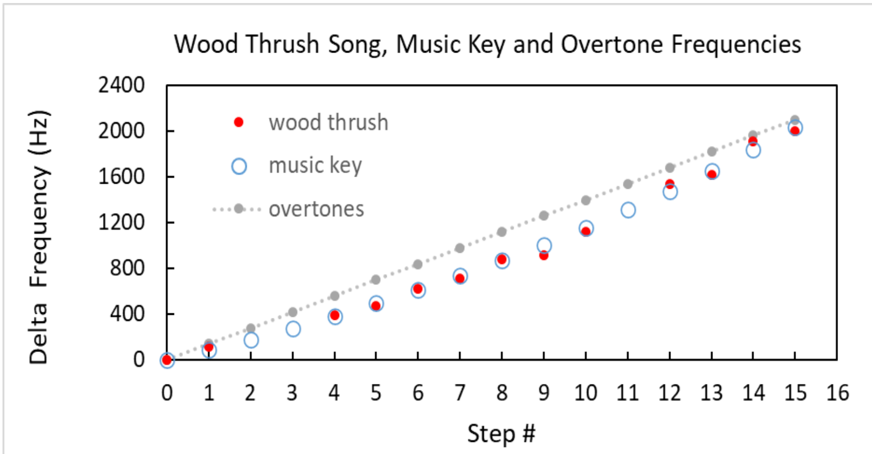
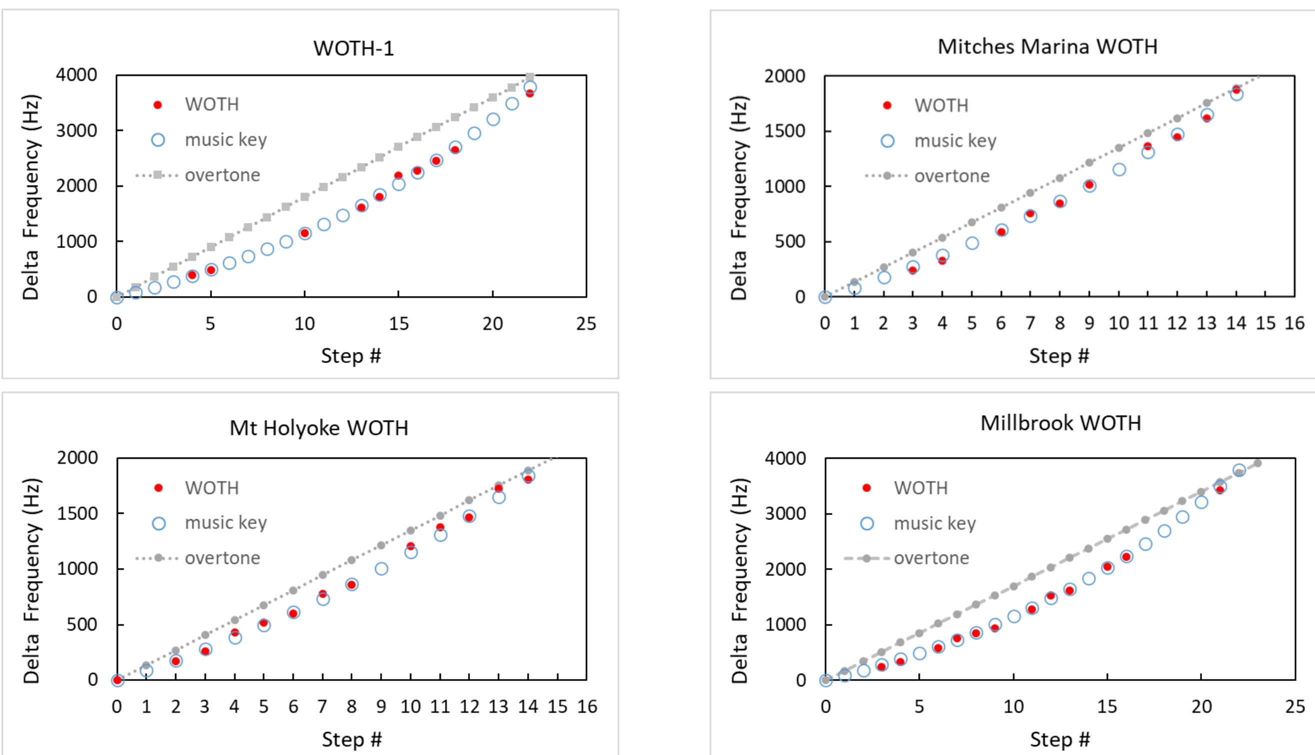


Fig. B2. Music key and *WOTH-2* '*p2*' song frequencies and overtones of a 140 Hz fundamental frequency above F#6 key vs. step #.



ig. B3. Music keys and *WOTH-1 and other three Wood Thrush* '*p2*' song frequencies and overtones of fundamental frequencies above F#6 key vs. step #.

Other Wood Thrushes showed similar preferences to music keys as shown in Fig. B3. The fundamental frequencies of the overtones for these recordings are in the range of 135 – 180 Hz.

It is fair to assume that the songs produced by a Wood Thrush establish his identity and thereby announce his presence to other Wood Thrushes in the neighborhood. They must be pleasing to himself and his mate. Additionally, his music pleases humans as well and helps us connect to nature on a common ground.