Zebra Finches (1) - What and how Zebra Finches really sing

12 Zebra Finches singing in an aviary (male and female)
2x-4x-8x slowed down with spectrogram and notation

text to the video : https://youtu.be/0eK9--aq3fA

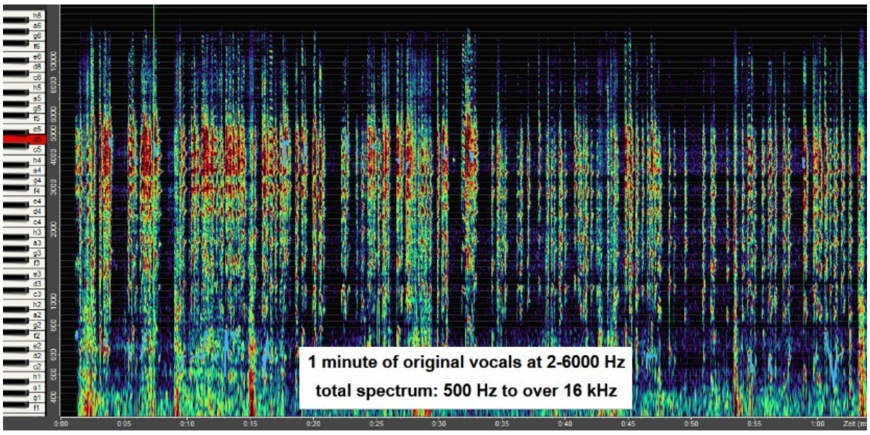
An Introduction to the Miracle World of Zebra Finches' Spectral Sounds

"Music is the hidden arithmetic activity of the soul, which is not conscious that it is calculating."
(Leibniz)

Subjects:
- How can we even “understand” the singing of Zebra Finches?
- octaving slow down in pitch and tempo with spectrograms of the Overtone-Analyzer
- The calls of Zebra Finches are complex spectral sounds that are interconnected and correspond in the spectrum.
- spectral sounds and their analysis
- Spectral sounds are produced in songbirds with both parts of the syrinx
- the ear as a spectrum converter (in birds and humans)

Appendix
1) 7 spectral sounds: F#5 – F#5 – D5 – D5-G5 – G5 – D5 – D5 (p. 11)
2) 8 sequences of spectral sounds from several Zebra Finches (p. 17)

In this video you can see and hear 6 pairs of Zebra Finches hopping back and forth in constant movement, apparently having a great time "talking to each other". It is a continuous sequence of different calls and sounds, sometimes brighter and sometimes darker, a little deeper or higher, all very intense. Some phases are very active, others a little quieter. It seems as if there is a very lively rhythm in which all 12, male and female (!), react to one another.
In a comment on the YouTube video someone wrote that his Zebra Finches were very excited and interested when he played the video to them. They obviously understood their fellows and were inspired by their "conversation".



The strange thing is that with our kind of perception, on the one hand, we actually only hear a random sequence of strange noises that we cannot identify or describe, and on the other hand, we tend to hear in these sounds a kind of conversation or communication between the 12 Zebra Finches.

The question is therefore whether we can find out how the Zebra Finches communicate with each other using their type of vocalization and their way of hearing, and also whether we, with our perceptual abilities, even have the opportunity to analyze, describe and even in a certain way to understand these sounds.

The calls of the Zebra Finches are very short (0.08-0.15 s) and sound in the range between 2500 and 5000 Hz. This shortness and the high frequency range acoustically exceeds our ability to distinguish between them. If we think we hear a kind of melody in the song of a Blackbird, these are significantly longer tones in the range of 1500-3000 Hz, where our hearing can just

distinguish between pitches and tone sequences. We hear all sounds that sound faster and in the higher frequency range as chirping, i.e. actually as a kind of noise and not as pitch or sound. Since the video was recorded in mp4 format, only frequencies up to 16 kHz are reproduced in the spectrogram. (With the wave format, the recording spectrum extends up to 22 kHz.) Since Zebra Finches often have a stronger sound intensity even at 13 kHz, I assume that the overall spectrum of their sounds is even larger than 16 kHz.
If to our ears, however, this "conversation" among Zebra Finches sounds like a random series of noise-like sounds, can we even “understand” the calls and songs of these birds in any way?

"Music is the hidden arithmetic activity of the soul, which is not conscious that it is calculating." (Leibniz)

In a major triad (C-E-G) a mathematical ratio of partial tones is formed (4 : 5 : 6) - we experience this as pure, harmonious, clear, bright, encouraging, etc.
In a minor triad (C-E♭-G), the minor third "E♭" rubs against the "E" of the major third as a partial of the fundamental tone - we perceive this as not so much "durus" (hard), but rather as "molle", soft and somewhat wistful, touching, etc.
A fifth (the ratio 2:3) sounds open and empty to us in harmony, a fourth (3:4) sounds denser, more compact; in an interval sequence, a fifth opens into a wide space, while a fourth pushes into active movement.

(If a tone vibrates at 200 Hertz, then the so-called "pure" fifth vibrates in a ratio of 3:2, i.e. at 3oo Hz, and the fourth vibrates to the fifth in a ratio of 4:3, i.e. at 400 Hz, the octave to that sound at 200 Hz, i.e. in a ratio of 2: 1. Our ear/brain "calculates" this very precisely and registers the smallest deviations, which we may perceive as inconsistent or as a special stimulus.)

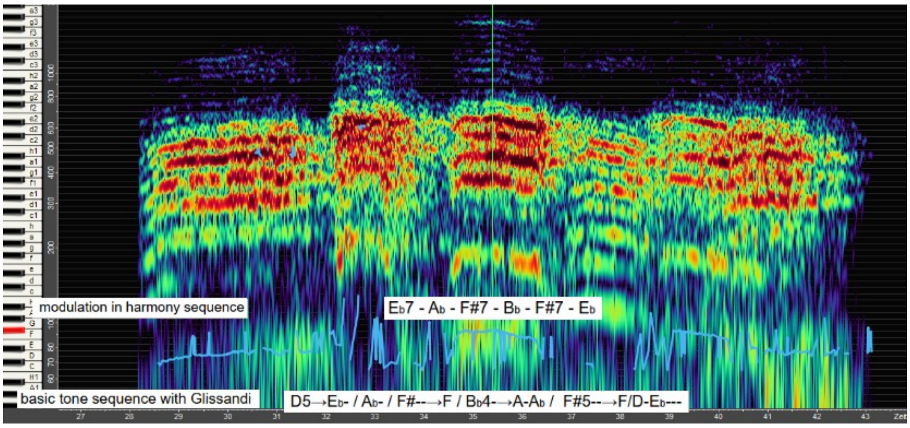
octaving slow down in tempo and pitch

If the calls and songs of the birds are slowed down by an octave (50%) in tempo and pitch, 2x, 4x, 8x and 16x, they are transposed, for example in the case of the Blackbird from F7 to F6, F5, F4 and F3. Through the octave transpose (1:2) downwards and the octaving slow down in tempo, nothing changes within the sound and/or noise in the structure (pitches, volume, intervals, sound figures), in the vertical layering and distribution of the frequencies as well as in the temporal and dynamic proportions. But what changes more and more the deeper and slower the sounds are heard is what we hear about it and in it and how we hear it. We hear more and more in each deeper dimension – more sound, more timbres, more spectrum, more variety, more clarity.
And in the lower frequency ranges that are appropriate and familiar to our hearing, we also hear different and different things in every position and in every sound range, some things as strange and unusual, even though they are physically and acoustically the same sound.
With the Blackbird, with its highly complex song, you can only recognize and understand what and how it actually sings when it is slowed down 16 or 32 times.

In the spectrogram on the Overtone-Analyzer (logarithmic, not linear! see below) I can see at first glance in the slowdown what kind of sounds I am hearing, a certain pitch, a sequence of notes, glissandi, 2-part sounds, trills, spectral sounds, etc. And I can determine exactly at what frequency not only the fundamental tone vibrates, but also every single partial frequency in the spectrum of a sound. For 2-part sounds I can calculate exactly whether it is, for example, a fifth in a ratio of 2:3. To do this, you can see directly from the color in the spectrogram and read from the volume value which partials are louder or quieter, which is crucial for the timbre and character of the sound. Finally, you can look into a sound spectrum in great detail using a vertical and horizontal zoom.

Spectral Sounds of Zebra Finches

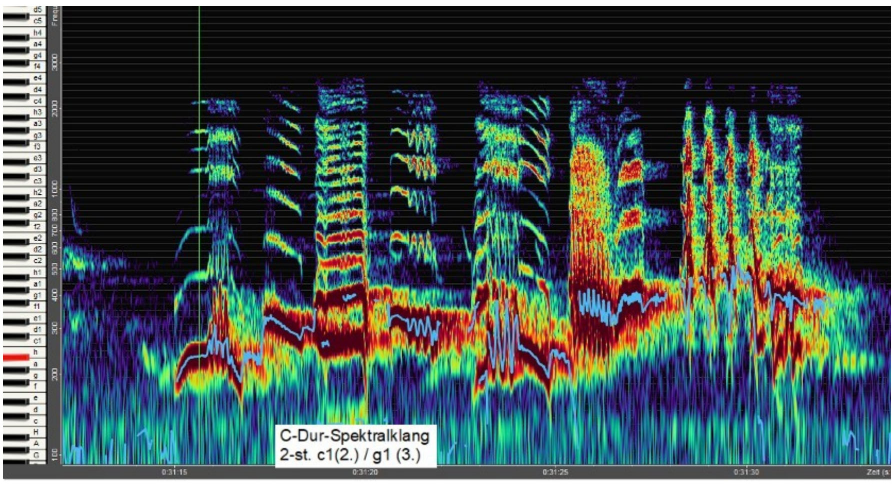
When I looked at the group song of these Zebra Finches for the first time in the spectrogram in the original position, I immediately noticed that there are no simple tones with a clear pitch and no sounds with a distinctive fundamental tone, but that all sounds have their greatest intensity at a higher frequency range between 2500 and 5000 Hz or at 3-6000 Hz. As I realized to my surprise during more detailed analysis, the Zebra Finches consistently produce spectral sounds.



Group song of 4 Zebra Finches: only very weak or virtual fundamental tones, corresponding in the spectrum

In contrast to noises, all sounds have a frequency spectrum in which all partial frequencies have an integer ratio to one another (1:2:3:4:5:6:7:8:9 ...). If the 1st partial or the fundamental is a C, the 2nd partial is the octave C', the 3rd is the fifth G', the 4th is the 2nd octave C'', the 5th is the third E'', the 6th is the fifth G'', the 7th is the seventh Bb'', the 8th is the octave C''', the 9th is the ninth D''' etc. This spectrum can be seen at a glance in a spectrogram record and it can be counted out exactly which frequencies, at what volume and up to which range vibrate in this sound, i.e. are parts of a whole (!). The sounding pitch is usually the fundamental tone when it vibrates loudest as the 1st partial, while the volume becomes more or less weaker with the higher partials of the sound (usually from the 4th partial).

The proportions between the frequencies within the spectrum always remain the same, even if a fundamental tone is originally at 3000 Hz and in the 8-fold slowing down at 375 Hz. A fifth always remains a fifth, regardless of whether it is in the ratio of 2:3, 4:6 or 6:9. For the fundamental note C, the interval C'/G' (2:3) is a fifth like the interval G''/D''' (6:9), even if one fifth comprises 100 Hz and the other 300 Hz (at C=100 it is 200:300 one time and 600:900 the other time). And when a Blackbird sings a 2-part fifth with B6/F#7 (2 kHz/3 kHz), the frequency range is even 1000 Hz, but we still hear these two tones together as a fifth and the Blackbird apparently does too, otherwise it couldn't sing such a fifth so precisely. This is the logarithmic, non-linear order of sounds, which is exactly displayed and reproduced in the spectrogram of the Overtone-Analyzer.
(In the sonagrams used in bird song research, the frequency scale is incorrectly displayed linearly, on a 1000 Hz scale, which is inconsistent with the internal structure of the sounds and their integer proportions.)



For comparison, the verse of a **Blackbird**: Spectrum of the song - G6 to G7 (1.5-3 kHz), full total spectrum up to 16 kHz / all sounds with a very strong fundamental tone / 2-part "C major" spectral sound with a virtual fundamental tone C6 and the sounding fifth C7/G7 (S1/S2 = 2./3.), in the common spectrum precisely coordinated
In the spectrogram you can immediately see that the C6 spectral sound is a 2-part sound and the lowest sounding note C7 is not the fundamental tone. Directly before this, the Blackbird sings a clearly unison

glissando from E7 to C7. From the structure of the spectrum of this C7 you can see that C7 is the fundamental tone with C8, G8, C9, E9, G9 and Bb9 as the 2nd to 7th partials. In contrast, with the 2-part sound, the C7 is immediately followed by the equally intense fifth G7, which can therefore only be produced by the 2nd Syrinx. At C6, the virtual fundamental note for this 2-part fifth sound is displayed.

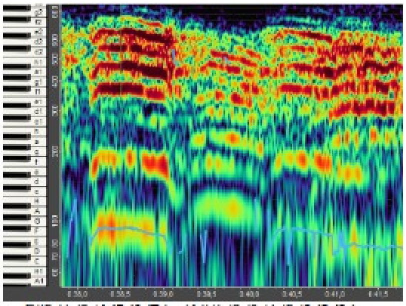
Spectral Sounds

With *spectral sounds* the fundamental tone is usually very weak and the first partial tones are also relatively quiet. The most intense frequencies are in the range between the 4th and 10th partials (2nd octave and 2nd third); sometimes there are 2 and sometimes 3 partials next to each other or on top of each other, which have the greatest dynamic level. This can be the triad octave/third/fifth (4:5:6), the 5th-6th-7th (third/fifth/seventh), the 6th-7th or the 8th-9th partial tone. These partials are then more than twice as loud as the fundamental tone, and sometimes even four times louder. And there are spectral sounds in which no fundamental tone sounds at all, but only the higher spectrum. This is then a *virtual fundamental tone* that the Overton-Analyzer displays exactly for the corresponding spectrum, even though it doesn't physically exist.

As already mentioned, all zebra finch calls and sounds have only a very weak fundamental tone. Only an excerpt from the spectrum of these sounds can be heard and yet the respective fundamental tone can be clearly perceived in all sounds. In the video I have selected 7 individual spectral sounds from the group song and made each one audible and visible in the spectrogram with notation. For example, the spectral sounds with the fundamental F#5 and G5 are missing the 1st and 2nd partials (fundamental and octave), while D5 is missing the 1st, 2nd and 3rd partials, i.e. also the fifth.
If we only heard the 1st and 2nd partials at a sufficient volume, it would almost be a sine tone, we would recognize the pitch sufficiently, but we would not be able to classify it reliably because no spectrum is stimulated in the ear (the cochlea!). As an experienced singer, I could imagine a third or a fifth to such a neutral sound and also sing to it, but this requires a process of learning and training in the cerebrum. The cochlea itself cannot think up or fantasize a spectrum for this tone. (see below on hearing and singing in humans)
If a zebra finch only heard these 2 or 3 frequencies of a tone (1st - 2nd - 3rd partial) from another finch, its hearing would hardly be able to orient itself due to a lack of stimulation and it would not be able to establish a clear relationship to such a neutral sound with its song. (This is no different for us humans. see below) If, on the other hand, the auditory system (in zebra finches and humans) is stimulated solely by the frequency spectrum in the octave between the 4th and 8th partials, these *partial frequencies represent the overall sound with its corresponding fundamental tone in their proportions and structure*, even if it does not vibrate as the 1st partial. The ear finds the fundamental tone in the integer structure of this spectrum of octave-third-quint-seventh-octave, regardless of how strong the individual partial frequencies are or whether the fifth and seventh are louder than the octave.

We have practical experience with this every day when we make phone calls. Only frequencies of 300-3000 Hz are transmitted on the telephone (analog - digital 300-7000 Hz) because physicists have discovered that this frequency range is sufficient to communicate with each other intelligibly, which means that a lot of transmission power can be saved. Nevertheless, everyone on the phone understands me and hears that, as a man, I have a deep voice, even though my speaking pitch is around 120 Hz. I can also sing a song on the phone in the range of 110-220 Hz and everyone hears exactly these low tones in my voice. And that's not all: My partner immediately hears how I'm feeling and what mood I'm in when I call her. That means she hears what my voice sounds like, what timbre and expression it has, i.e. everything that resonates in the spectrum of the voice. Conversely, the same applies to my partner, whose female speech range is 220 Hz.

Explanation: In the spectrogram of my voice on the phone there is no spectrum below 300 Hz, instead the complete spectrum from 300-3000 Hz, but the pitch marker shows exactly the pitch of the spoken words and the sung melody in depth. Conclusion: Our ear recognizes a weak and colorless sound as weak and colorless (= little spectrum) and at the same time has the innate ability to extract a lot of information from the high spectrum of the sound (!) or timbre of speech. And when it comes to pure sounds, the ear has the same innate ability to calculate the pitch of the fundamental tone from the structure of a spectrum.
(→ "Sound spectrum of speaking and singing voice" : https://youtu.be/C5uBeCkFHn4)



F#5 (1./2./**4./5./6./7.**) - (A#4) (2./3./4./5./**6./8./9.**)

I found a wonderful example of the effectiveness and potency of the higher frequency spectrum in the video in a sequence of spectral sounds from 4 Zebra Finches (left image excerpt). One sings an F#5 sound (= F#7) with an intense spectrum at F#7/A#/C#8/E (4./5./6./7.). You can clearly hear a full colored F#5 sound. With the other, you surprisingly hear a sonorous tone a sixth lower, although the high spectrum is not very colorful and the low tone at A#4 doesn't sound at all and is not even shown by the pitch marker as a virtual fundamental tone. In the spectrogram you can only see relatively weak frequencies in the 2nd to 5th partials and slightly stronger ones in the 6./8./9. partial tone. The A#7, the third (5.) of F#5, is identical to the octave partial (8.) of (A#4). Another finch probably responds to this much more quietly with the same F#5 sound as the first finch, now with a virtual fundamental, and another finch responds with a (D#5), a virtual fundamental also with a spectrum from 4th to 7th partial (= D#7), in which the fifth partial A#7(6.) is identical to the previous frequencies.

It's hard to believe when you see the spectrogram and then hear the sequence of sounds, first the low sixth and then the minor third: *F#5-A#4-F#5-D#*. I hear the movement of the fundamental tones, but the inner workings or the inner life of the sounds, the wave movements of all frequencies and the sliding of the spectra, their dynamics, their various states of excitation and their interaction take place in the high frequency range between the 4th and 8th partial tone.

And when I played the entire sequence with its 6 spectral sounds in their harmonic sequence on the piano, I was completely overwhelmed by its beauty and the wonderful harmonic order:
Eb7 - Ab - F#7 - Bb - F#7 - Eb
basic tone sequence with small Glissandi: D→Eb5--/ Gb-Ab6--Gb / F#5--→F / Bb4-→A-Ab / F#5--→F / D-Eb5---

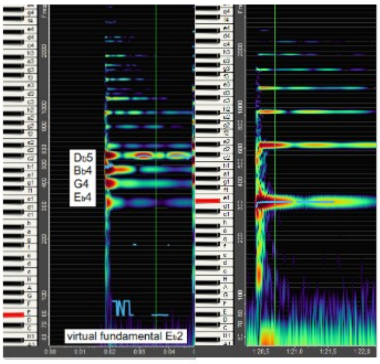
Harmonic order: fifth relationship E flat major - A flat major / (A flat major = G sharp major) from G sharp major to the double subdominant F#7 and then not to B major, but to the upper mediant A# major (= Bb major) / back to F#7 and further into the lower mediant D# = E flat major. This could well be the idea of a 19th century composer. (the whole sequence with spectrogram p. 17)

The elementary complexity of the spectral sounds of zebra finches, their *complementarity, correspondence and connectivity* has the same basic level as many complex sounds that can also be heard in more highly developed songbirds such as the blackbird.

In the sequence of the spectral sounds, the modulation cannot naturally be heard as clearly or pure, on the one hand because the spectral sounds always have a slightly noisy quality to our ears due to the density of the partial frequencies, and on the other hand because the sounds of the birds are always in motion, in the semitone Glissandi, in smaller up or down movements or in a stronger vibrato. They are extremely lively vocalizations that express a vegetative state of excitement (vagus nerve→syrinx) and at the same time have a stimulating effect on the basic vegetative excitation via the hearing (ear→syrinx→vagus nerve).
This process of interaction applies to the ear/syrinx/vagus nerve system in each individual bird, to the effect from bird to bird, and to the acoustic field and arousal level of the entire group.

I know the interaction between hearing, voice and vagus nerve well from my own experience with my own singing, listening to singing voices and experiences with birdsong. It is the high vibrational energies in the sound of my voice (brilliance formants around 3000 Hz and higher) that are an expression of the efficient regulation of sound production and how it increases the efficiency of the vibration in the vocal folds in a control loop (a *self-organized process*). I don't just hear these high vibrations in the sound, I feel them in (!) my ears and I specifically feel them as vibrations in the ear canals. (In the ear canals, the brilliance formant is amplified by 3000 Hz due to acoustic impedance in tubes.)
I have a similar feeling when my ears are stimulated by the brilliance of other singers' voices. After hearing such voices, my singing has a higher energy level. And it's no different with many bird songs. When I listen to intense bird song, I often experience the chirping, high-energy sounds

literally entering my ear canals, causing intense turbulence. Such experiences always have a direct effect on the vegetative mood of my organism, a feeling of lively excitement.
When I discovered this amazing harmonic sound sequence in the 6 spectral sounds, which also means that I listened to them again and again, I was completely moved and physically excited by this discovery alone (breathing, heartbeat). But when I finally found out what the Zebra Finches are actually singing, what an incredible modulation it is, and then played the pure extract of this sequence in the simple chord progression on the piano, I was overcome with such excitement that my heart wasn't just pounding but my pulse went extremely high.
When I played this harmony sequence on the piano for my partner, without her knowing what it was, she spontaneously said: "That sounds beautiful!" This sequence of 6 chords obviously exerted a strong stimulus not only on their ears due to the special type of modulation, but also directly on their sensory feeling and their preconscious sense of pleasure, before any aesthetic evaluation or classification. Every acoustic perception is filtered (pleasant / unpleasant - fear / lust) in the limbic system before it reaches the auditory cortex.
So much for the interaction between hearing and the vagus nerve. Analogies to the mood in group singing of Zebra Finches are probably obvious.
→ “The control circuit of vocalization vagus nerve hearing” :
https://www.entfaltungderstimme.de/pdfs/Control-Circuit_Vocalization-Vagusnerve-Hearing.pdf



In video appendix 3 you can hear this chord progression on the piano, alongside the singing of the finches. In the spectrogram of the piano sound you can see that there are two corresponding partials in all spectral sounds: Eb5 and Bb4/A#4. They are the link between the sounds in the spectrum.
In the picture on the left, the spectrum of the Eb seventh chord is next to the single note Eb4. In terms of the spectrum, the sound of a finch could look like this, which it produces with 1 membrane, the fundamental note Eb4 with its partials (2.-6.). On the other hand, the spectrogram of the Overtone-Analyzer analyzes the seventh chord Eb4/G/Bb/Db5 (4.-7.) as a spectral sound with a virtual fundamental tone 2 octaves lower at Eb2 - according to the same model as the spectral sounds of finches are analyzed.

The Overtone-Analyzer "hears" (analyses / calculates) the spectrum of the seventh chord in the sound of the piano using the same model as our ears hear / analyze / calculate a sound in its spectrum. That's why I can recognize and hear the fundamental tone of a seventh chord, regardless of its position, and then sing it in my own voice range. This also applies to any inversion of the seventh chord if the fundamental tone is not the bass tone of the chord (G/Bb/Db/Eb or Bb/Db/Eb/G or Db/Eb/G/Bb). And just as well and with a little experience, I can sing a seventh chord as a sequence of notes to a single note that I hear from the piano (to Eb: Eb-G-Bb-Db).

Two clarifications:
1. In all vertebrates, vocalization is innervated (purely sensorial!) by the 10th cranial nerve, the *vagus nerve* , i.e. the larynx in humans and the syrinx in birds. There is no direct muscular control of the larynx or syrinx by the cortex. In humans and birds, there are not only afferent pathways from the cochlea to the brain, but also efferent pathways from the formatio reticularis in the brain stem to the cochlea, which generate effective basic excitation in the cochlea. In humans, these cochlear efferents are known to stimulate the outer cilia (sensory hair cells), which can be measured as otoacoustic emission or as electric excitation potential.
The vagus nerve innervates the larynx/syrinx and ear canal, heartbeat, breathing, digestion and sexual arousal.

2. The so-called overtones are not "above" or "higher" in the real physical sound spectrum than the so-called fundamental tone, but are, as partial frequencies, elements of one (1!) sound, a multidimensional, multi-layered and complex structure in space and time with a specific energy. All frequencies from 1st to 16th/64th/128th ... partials oscillate in (!) this one (!) sound. Spectral analysis makes it possible to hear and look into the inner life and into internal structure of a sound via the spectrogram. *Sound is the unity of space and time.* And as with all systems, the sentence applies:*“ The whole is more than the sum of its parts”*.

The Ear as a Spectrum Converter

As a *spectrum converter*, our hearing is able to convert the specific structure of a spectrum into pitch perception, which apparently also applies to songbirds. I can sing the corresponding pitch of the fundamental tone of such a spectrum by ear (in my voice register), without having heard it before and without knowing which tone to sing. I don't need a pitch indication, a definition of that tone, or a harmonic analysis.

Just a quick note: I consider the common model of hearing as a "pitch recorder" to be at least limited, if not wrong, according to which information about pitch is passed on via the cochlea to the hearing center in the brain and there in a tone topological arrangement is processed. Just as there are no specific colors outside the brain and eyes, there are no individual tones “out there” with a specific pitch. There are no sine tones in nature, what we perceive as tones are sounds with a certain spectral pattern.
"'Out there' there is really neither light nor color, there are only electromagnetic waves; 'out there' there is neither sound nor music, there are only periodic fluctuations in air pressure." (Heinz von Förster)
(→ “The control circuit of vocalization vagus nerve hearing” :
https://www.entfaltungderstimme.de/pdfs/Control-Circuit_Vocalization-Vagusnerve-Hearing.pdf)

As I have documented in this video, Zebra Finches (like all songbirds) don't have perfect pitch, they do not need the names of tones, no idea of pitches and no theory of harmony. Whether in calls or in song and regardless of the level of development of their song, they are all oriented towards the spectrum structure of their sounds.
They repeat exactly the same spectral sound at different stages of their communication; they sing the same sound at the same time as another; they take up a spectrum and lead it into another sound, which in turn is related to the previous sound via certain partial frequencies; they let a D major D7 sound from one finch be followed by a G major sound from another finch; 4 or 6 finches form coherent sequences of spectral sounds that are put together and interwoven in such a way that all spectra are related to each other; they react in a modulating manner to the sound of another while singing; or even correct themselves if the coordination of the two membranes does not work.

All vocal utterances of this group of zebra finches are thus related to each other via the spectral harmonic order of the sound. This sound order forms a kind of *matrix of their vocal communication*, which does not only consist of responding to an F#5 sound with a D5 sound or continuing the D5 sound of another finch with a G5 sound. For the conversation in the group, it seems to be quite obviously not only interesting who reacts with which sound, who responds to this or that or who sets a new sound impulse, but (above all?) also *how it sounds*, how it is intoned, what color and what coloring a sound has, brighter or darker, more open or denser, fuller or finer, more intense or more subdued and much more. The special thing about the spectral sounds of songbirds is that all these polarities, the most diverse elements of timbre and sound quality can also be present in a single spectral sound at the same time, can appear as nuances or facets of a sound, *opening up a wide range of expressive possibilities*.

And to make this clear too: *males and females* apparently participate on an equal footing in this type of communication or sound conversation. In the YouTube video I could see one of the females' throats expanding several times when she made a sound. There is no difference in the spectrogram that could indicate that the females have special calls. And from the video "Zebra Finches (2) - Male and Female" I know that the females have wonderfully sonorous spectral sounds in their repertoire.

Spectral Sounds are produced using both Parts of the Syrinx

With their double syrinx, all songbirds have the ability to produce spectral sounds that occur when the membranes of both parts vibrate at the same time and are more or less coordinated with each other. Even very young birds in the nest produce multi-colored spectral sounds without a fundamental tone, which sound rather noisy to us when slowed down, but which probably express a mood or excitement to the parents. Even the cawing of a crow is a multicolored spectral sound and, when slowed down, sounds to me like a very impressive glissando sound, but without any information about pitches. From a crow I discovered the most beautiful 2-voice fourth in the slowdown as a sound I have ever heard in music. (Which proves that crows are also songbirds by nature).

When Zebra Finches vocalize, both membranes are usually activated simultaneously, and when two sounds interact, they produce a specific spectrum controlled by hearing. By comparing and analyzing 7 spectral tones (see page 9), I found that the interaction between the two membranes can also be more differentiated. So syrinx 1 (S1) can begin with a small ascending glissando and S2 then begins with a progressive main sound. Depending on this, the sound is not simply amplified, but the intensity can shift at different frequencies. So it's not a simple volume effect. Even if both membranes seemingly begin at the same time, in the sounding of both spectra there is always *a flexible, moving process of correlation, coordination, dynamic accumulation or attenuation in the structure of all partial frequencies*.

The fourth spectral sound of the seven selected sounds becomes even more complex. S2 begins with its own short turn, which leads S1 alone into the main sound. Then S2 starts up again on the main sound, modulating the overall spectrum slightly, and when S1 ends the sound, S2 lets it continue sounding a bit. (You can listen to this interplay between S1 and S2 in appendix 1 of the video.)

The complex interaction of both membranes becomes very clear in the example of "sound sequences" (p. 18) when a finch modulates its B♭5 sound while singing (!) in such a way that it matches the spectrum of the E♭5 sound of another finch. Both membranes allow the corresponding frequencies of B♭ and E♭ to continue sounding, while others slide into the other spectrum - *a marvel of coordination* between both parts of the syrinx in one sound. (p. 18)

And immediately afterwards you can see how another finch really fails to coordinate both membranes in its own spectral sound, even though it tries to do it twice, i.e. it immediately hears that something is wrong. (p. 18)

Spectral sounds in a much more complex form can be found in Blackbirds, Robins, Larks and Starlings, among others. In all birds, in their original position, they can only be heard as unspecific chirping, if at all. Some of the sounds of these birds that our ears interpret as tones are actually spectral sounds that are produced by both parts of the syrinx.

A true master of spectral sounds is the Dupont-Lark (Chersophilus duponti), which can conjure up modulating Glissandi in full sound using pure spectral sounds without a fundamental tone (e.g. from a D major septnon chord into a D major triad F#/A/C/E → D/F#/A). Or: First a C fundamental tone sounds in S1 and then with S2 an A flat spectral sound is added to the C, the submediant to "C major" and an A flat major spectral sound without a specific pitch is heard.

When a Blackbird sings a 2-part fifth, third or seventh, these are two independent vibrations with their specific spectrum, but which are coordinated with one another in such a way that both basic tones are in the exact ratio of a fifth (2:3), a third (4: 5) or a seventh (4:7) and thus form a common, consistent spectrum of all partial tones, which in turn can have its own unique timbre. (see the spectrogram of the blackbird's song above) The Blackbird then sings a perfect fifth or a "natural seventh", but that does not sound like a 2-part interval, similar to the one on the piano, but rather all the other frequencies of these two voices vibrate more or less, and this results in a true *spectrum of colors* in the sound.

To get an idea of the sound character and timbre of a Zebra Finch's spectral sound, you can play the following notes together as a chord on the piano for a spectral sound with the fundamental note D3: F#5/A/C6/D/E. These are the partials 5/6/7/8/9.
For a 2-part spectral sound of a Blackbird, this could be the seventh F/Eb, which I analyzed as my first discovered spectral sound. The basic interval plays F3/Eb4 and the notes A5/B♭/C6/E♭/G 2 octaves higher. These are the partials 5/6/7/9 of F3 and the tones 3/4/5 of E♭4, whereby E♭6(4.) and G6(5.) are identical to the 7th and 9th partials of F3. Olivier Messiaen uses such types of spectral sounds without the fundamental tones in his “Bird Music”.

The ornithology books say that some birds can also sing in two voices due to the double syrinx, which is described as a particularly high art of singing, although bird song research has not yet been able to say what and how the birds actually sing. According to my analysis of the song of zebra finches (see the 5 videos below) and my previous research, it is probably more the case that <u>the natural and innate form of vocalization in birds is vocalization with both membranes in both parts of the syrinx</u>, in all of them noisiness, as we (!) hear it in the cawing of a crow, for example.

The spectral sounds of the zebra finches now show that, like many other songbirds, they have achieved a high level of coordination complexity through the interaction of both membranes, which enables *differentiated and multicolored communication between conspecifics* (male and female).

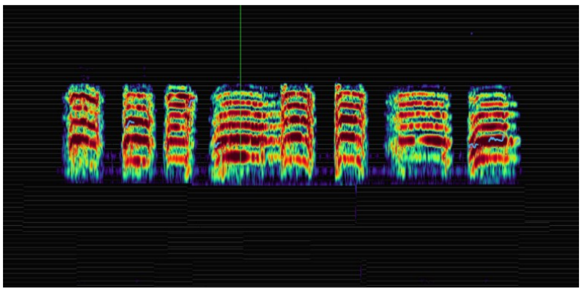
In real *2-part singing*, for example in the Blackbird, an independent vibration is generated in each membrane, with a strong fundamental tone and its own specific frequency spectrum. Both voices vibrating independently of one another can still correspond and agree in the spectrum structure in such a way that they form the common spectrum of a 2-part fifth or another interval. Amazingly, both voices (diaphragms/membranes) can also perform different independent sound movements, such as opposing glissandos, different types of interval trills, simultaneous tenuto sounds and gliding tones. However, all of these artistic singing skills move in a common and correlating spectrum, just like the real spectral sounds.

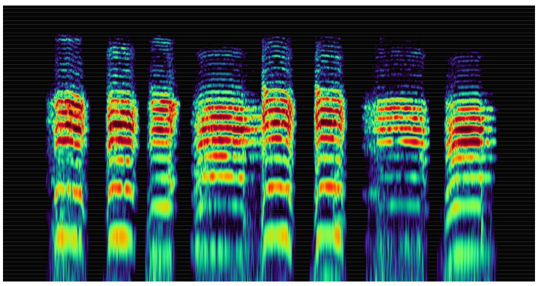
From my lessons as a singing teacher, I know that some people with insufficiently trained ears have difficulty picking up and singing a pitch from a single piano note with its low frequency spectrum. But if I sing the same note to them in a full colored voice (large spectrum with very high frequencies of over 3000 Hz), they can sing it spontaneously, even if their tone does not yet sound in the full spectrum. When people's hearing is stimulated in a variety of ways through hearing experiences with a colorful and high spectrum, they can orientate themselves better in sounds and tones, and then a larger spectrum of sounds develops in their voice. And that in turn has an effect on their hearing - *an effective feedback circuit*. Then every person can sing the "correct" and "clean" fifth to a full-sounding fundamental tone without trying to "hit" a pitch 5 tones "higher" than the "lower" tone. If the ears are effectively stimulated by the sounding fundamental tone with its entire spectrum, the ear involuntarily finds the fifth-partials in the sound spectrum of the fundamental tone (3rd - 6th - 12th - 24th partial), which the voice orients itself towards if it it intoned the fifth in correspondence with the spectrum of the fundamental, as a fifth and not as an independent fundamental. This is balanced by the ears during (!) the singing. When the correspondence is achieved, the overall sound and the voices of the fundamental tone such as the fifth receive a higher energy (!), which in turn stimulates the autonomic nervous system.
Humans and songbirds like the Blackbird can hear and sing a fifth because there is a corresponding circuit in their hearing/vocalization system, an innate gestalt understanding of sound structures like the gestalt of a fifth. It is the "unconscious ratiomorphic apparatus" (Konrad Lorenz) that calculates the vibration ratio of 2:3 from the sound, the pattern "fifth".

In the singing and hearing range we are familiar with, our human ears are primarily oriented towards the same spectrum range in which the Zebra Finches have their core spectrum, between the 4th and 8th partial tone, in which the octave, the third, the fifth and the sevenths oscillate as partial frequencies.

And songbirds also need *stimulation from the rapid oscillations of high frequencies* for their singing skills, for learning their songs and for communicating with their fellow birds, especially in the frequency ranges that are still above their singing spectrum, which in any case oscillate faster than that which our human hearing is able to recognize and which cartograph and defines our auditory concepts as pitches and tone sequences. The intense vibrations in complex spectrum patterns - this is the crucial *nerve nourishment* for energetically charging the autonomic nervous system (vagus nerve), the hormonal balance and all brain functions from the brain stem to the cortex.

Sound "Gestalt"





the pure Sound **the Variety of Spectral Sounds**

"Klanggestalten" (sound shapes) - atmospheric structures in space and time

without definition, without classification, without pitch

The filtered spectral sounds without a basic sound act like the concentrate of the calls of the Zebra Finches, sound events – the pure sound.
The complete spectral sounds in all their diversity seem more lively, more colorful, more complex, more expressive, more individual – they are vocalizations of living beings.

The sound is not only more grounded with its basic sound, it also has a dimension of depth in a multidimensional sense. And due to the high frequencies over the main spectrum from 6 to over 16 kHz, it has an energetic aura of the finest stimulation for the ears and the autonomic nervous system. In addition, the slightly noisy and rough parts of the spectrum reinforce the expression of excitement as well as physical and vegetative mood.

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see and listen to the videos:

- Zebra Finches (2) : male and female singing together : https://youtu.be/FOg1O3CogZ4
- Zebra Finches (3) - sounds and calls in a group of Zebra Finches : https://youtu.be/txgzXi3lCG0
- Zebra Finches (4) - sounds in a group of 6 male Zebra Finches : https://youtu.be/gnK3RHUTAYE
- Zebra Finches (5) - solo songs of 3 different Zebra Finches : https://youtu.be/dZ_6TB21yOc

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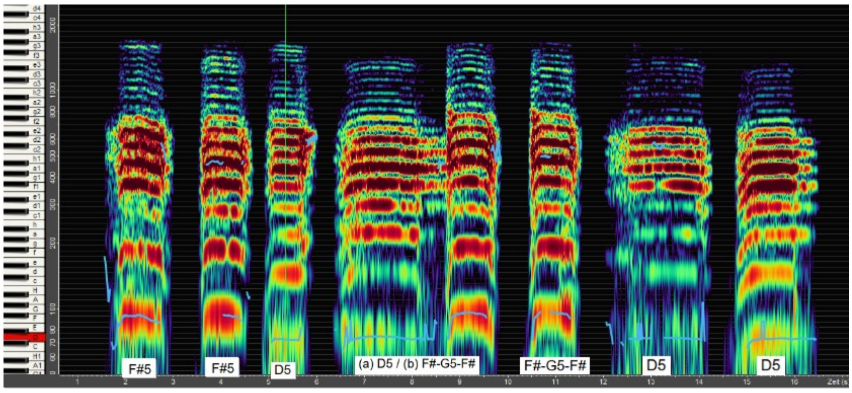
next page Appendix

Appendix

1) 7 Spectral Sounds
2) 8 Sequences of Spectral Sounds from several Zebra Finches (page 17)

7 Spectral Sounds: F#5 – F#5 – D5 – D5-G5 – G5 – D5 – D5

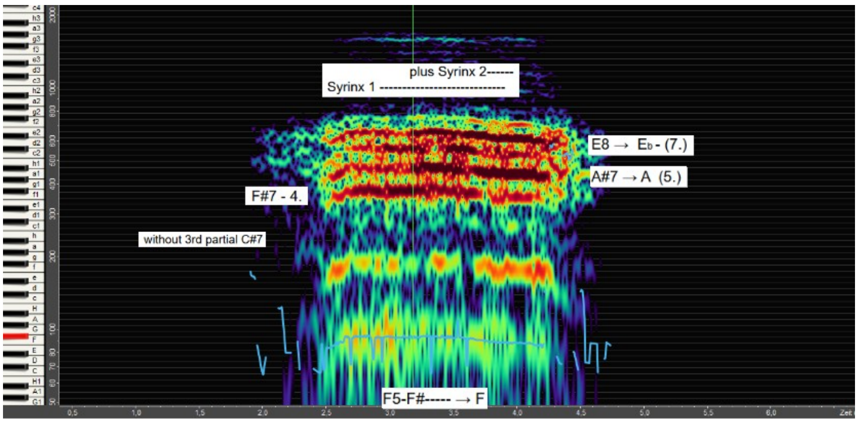
compiled in the order in which they appear



I chose these spectral sounds from the 77 sounds in the zebra finches' "conversation" for several reasons:
- They have a distinctive clear spectrum to be able to display and analyze the properties and qualities of the spectral sounds of zebra finches.
- Except for sound connection D5-G5, all sounds are produced by individual finches, without another finch reacting to the sound with its call.
- These 3 sounds with their basic tones D5, F#5 and G5 are the most common.

Even if the individual sounds do not appear in a direct connection, but come from different phases, you can see in their basic tones and in their spectrum that there are both connected basic sounds and common structures and orders in the frequency spectrum. It is a kind of *matrix according to which individual elements and a system are ordered and connected*: the elements of each sound (partial frequencies / fundamental tone), each sound as a specific vibration system (structure / dynamics / interaction of the part frequencies), the harmonical patterns in all sounds (octave -fifth-third...) and the system of communication / "conversation" among these finches (receptivity and activity in listening and singing / arousal dynamics / roles in the group). Everything is connected and interrelated with one another and with each other.

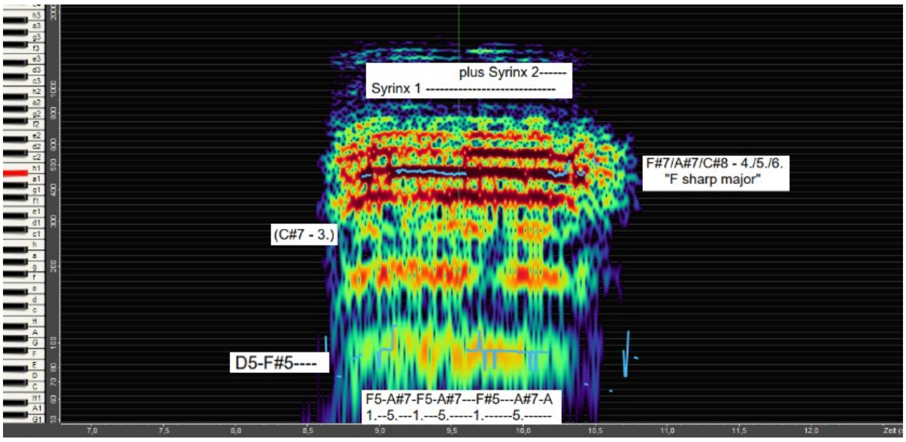
1) F#5 – halftone glissando F#→F------



partials: F#5(1.)-F#6(2.)-F#7(**4.**)-A#7(**5.**)-C#8(6.)-E8(**7.**)

Syrinx 2 starts a little later in exactly the same spectrum and amplifies the 5th and 7th partials.

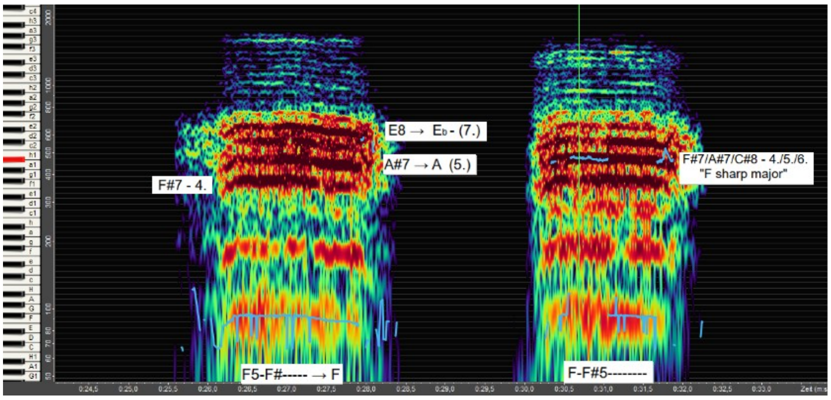
2) F#5



Syrinx 2 also starts with this sound later. The 5th partial A#7 is so intense that the pitch marker of the overtone analyzer jumps back and forth between the third and the fundamental several times.

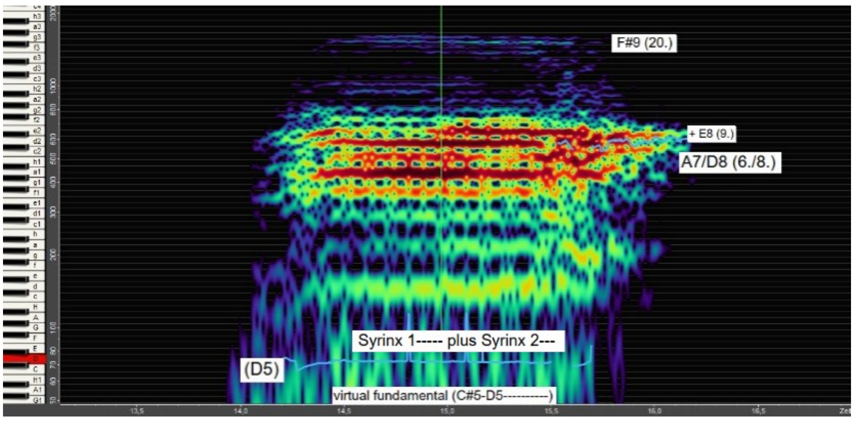
With the 4th-5th-6th partial tone actually sounds like an F sharp major triad. These are the 3 partials in the spectrum that are most important in determining the fundamental and sounding pitch of a sound. If you only hear the 3 frequencies in a filter, our ear clearly recognizes the correct, actually deeper fundamental tone.

both F#5 sounds in comparison



Both F#5 sounds next to each other with the same fundamental tone and almost the same spectrum: The second sound has a different timbre because the 5th partial is more intense (third A#7) and the spectrum has a stronger brilliance formant at 12 kHz (around F#9).
This sound appears fuller and rounder, especially due to the strong third from the beginning.

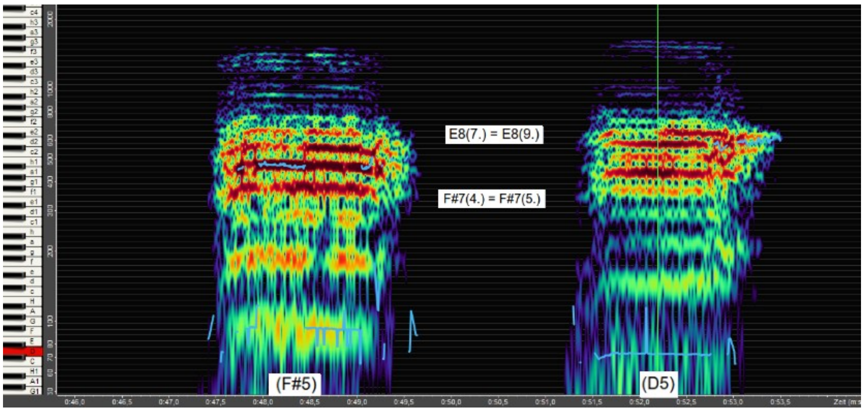
3) D5 with virtual fundamental



D5 – a virtual fundamental that does not physically exist.

Only the dominant frequencies A7 and D8 (6./8.) represent the basic sound. When Syrinx 2 also begins to vibrate, the 9th partial (E8) also becomes stronger.

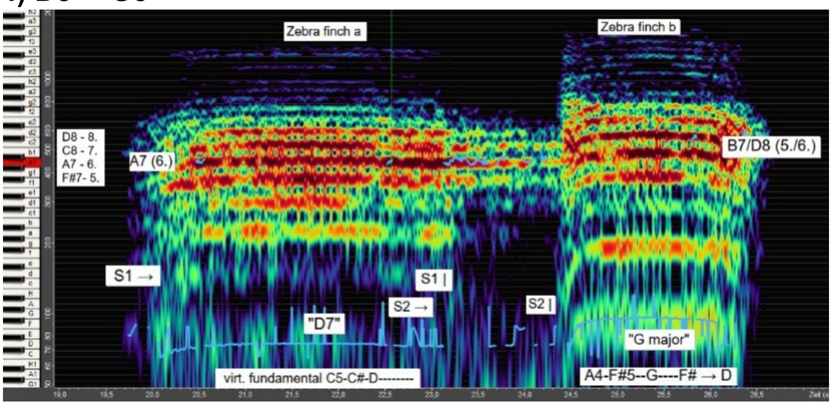
F#5 and D5 in comparison



The 2nd octave F#7 of F#5 is the third of D5 - F#7(4.) = F#7(5.) - and the seventh E8 of F#5 is the ninth of D5 (E8 is the double fifth to D6 - D:A:E = 2:3-4:6-6:9.)

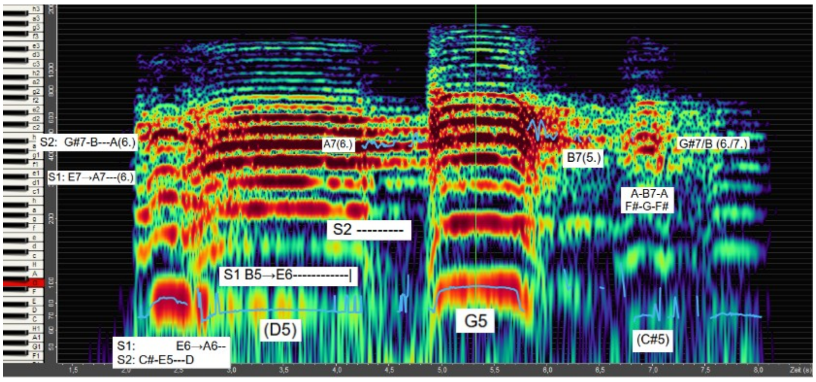
Although the D5 sound has a higher spectrum, it is clearly heard as a lower tone, even if you only hear the frequencies from F#7 to C#8 in the filter. At the first sound, the fundamental tone F#5 is only faint and at D5 it is barely audible.

4) D5--- G5---



First "Zebra Finch a" sings a D5 sound and then "Zebra Finch b" sings a G5 sound. Both sounds are not tenuto tones, but the D5 starts at C5 and slides over C# into the drawn out D, while the sound of the other zebra finch takes the fifth A of the D5 sound and slides from A4 over F#5 to G and at the end slides down to D5 via F# - **a:** C5-C#-D------ A7 - - **b:** (A4)-F#5--G----F#→D.
The D5 is clearly a virtual fundamental and in the G5 the 1st partial is very weak. The sounding spectrum of D5 is F#7(5.)-A7(6.)-C8(7.)-D8(8.), the loudest partial is the fifth A7. For the G5, G7(4.)-B7(5.)-D8(6.)-F8(7.) form the main spectrum, in which the third (B7) and the fifth (D8) are the dominant frequencies. The 8th partial of D5 (D8) corresponds to the 6th partial (D8) of G5.
In the first sound you can actually hear a seventh chord ("D7" - D5 with the seventh C8), in the second a "G major" triad is heard more clearly and in the sequence the fourth D5-G5 sounds. Since the fifth of D5 is very "dominant", all musical ears in this sound relationship immediately hear a D major dominant seventh chord (D7), which leads to the tonic G major. Musically, this connection is made even more interesting by the fact that the sounding D7 sound is actually a fifth sixth chord (the 1st inversion of a dominant seventh chord with the third in the bass), F#/A/C/D, whose diminished fifth F#/C strives in resolution into the G major third (G/B) of the tonic.

the complete sound sequence D5 - G5



In order to be able to represent this harmonious sound relationship a little more easily, I have initially left out what happens before and after. In short, "Zebra Finch a" makes a small intro to the long D5 sound, and after the response of "Zebra Finch b" there is a short C#5 sound with echo. It may be that another zebra finch briefly intervenes in the sounding conversation of "a" and "b", or "Zebra Finch a" makes a small follow-up comment on the interesting sound sequence. The amazing thing I discovered when analyzing it closely was that it's not just any "intro" at the beginning, but that first "Syrinx 2" *) starts with C#-E5--D and then "Syrinx 1" to that E5 begins with E6→A6---. With Syrinx 2 the complete spectrum of the fundamental tone sounds, but especially the fifth B7 (6th). At Syrinx 1 the frequency E7→A7(6th) is strongest, which then dominates the F#/A/C/D sound as a fifth.
What's even more fascinating is that where I inserted the "A7(6.)" you can see a small break in the spectrum and the intonation becomes slightly deeper, which can only mean that Syrinx 2 starts up again here and fits into the D5 spectrum. After Syrinx 1 ends, Syrinx 2 continues with an audible "D major" triad, into which "Zebra Finch b" intones its G5 sound. (an analysis of the spectrum of D5 in the appendix above)

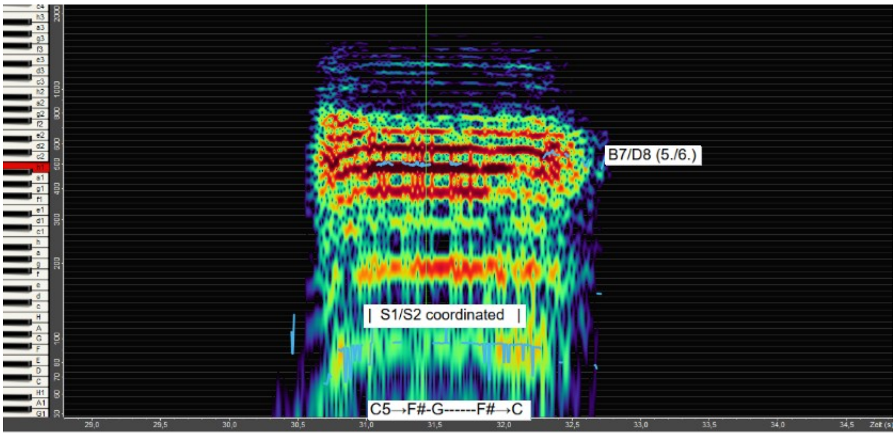
*) "Syrinx 1" is the secondary voice in this sound.

Starting with the E5 makes sense in a harmonic structure, because the E is the double fifth of D (D/A/E). And the sounding C#5-E---D can also be heard as an encirclement of the fundamental note D, i.e. from A major with a third and fifth to D major. The sounds in Syrinx 1 and 2 find their way to and into each other through a relationship through the fifth, a process that I have repeatedly observed and heard in birdsong.

The short "statement" at the end with the low C# probably comes from "Zebrafink a", because the C#5 as the virtual root note at the end is the same virtual C#5 as at the beginning. In the high sound spectrum, this short sound is a sequence of thirds F#/A-G#/B-F#/A. Afterwards, a very quiet echo can still be heard at C#5.

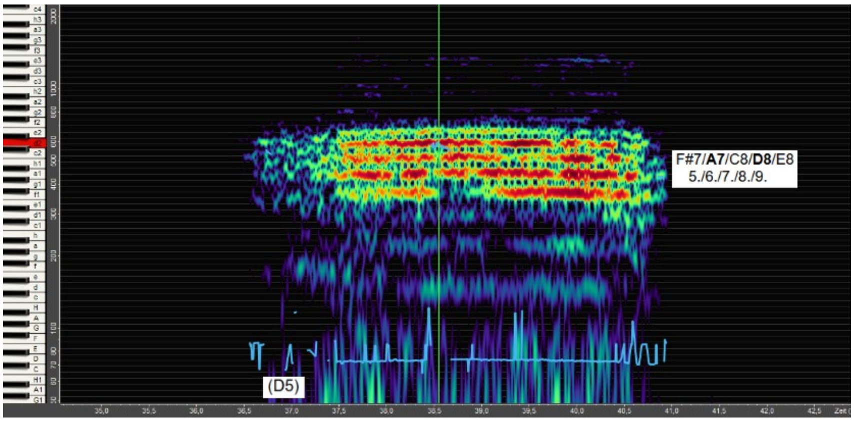
The overall sound sequence is: C#5-E--D------G---C#. If the G5 were only 3 Hz higher, both sounds would be in the exact ratio of 3:4 and we would hear a completely "pure fourth", which would not be so clear anyway due to the glissandi at the beginning and end of G5. The entire figure lasts 0.3 s in the original. That's how quickly and precisely the ears and voices of zebra finches can react and coordinate with each other!

5) G5 – C5→F#-G------F#→C



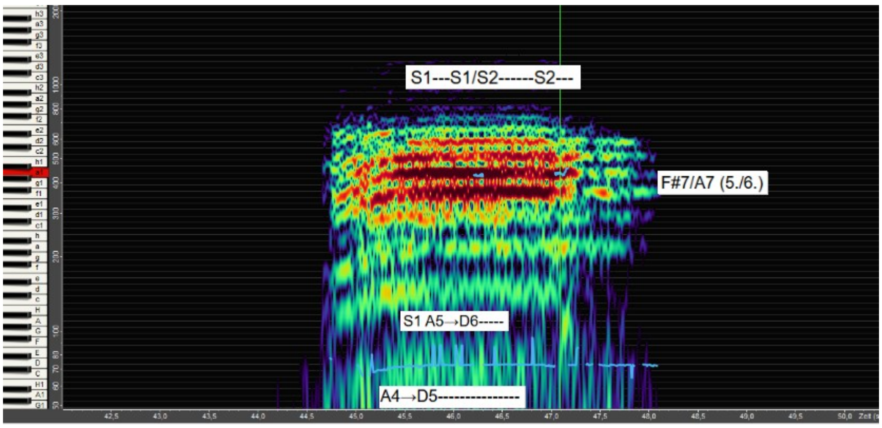
Syrinx 1 and Syrinx 2 do not start at exactly the same time and are only coordinated on the main sound G5. The most intense frequencies are the third B7 and the fifth D8.
It is a very colorful and powerful sound. When I hear it, I spontaneously sing the octave G3 in my vocal range. It is also very easy to intonate the third, in my position it is B3.

6) D5 – virtual fundamental



A spectral sound with a dense spectrum in a high register from the 5th to the 9th partial and a low fundamental tone D5, which can only be heard very quietly in the filter. All partial frequencies have a fine vibrato, which gives the sound a special character.
When heard and read harmonically it is a seventh chord in the 1st inversion with the third in the bass, a fifth-sixth chord. It is a deep sound with a shimmering color spectrum. The fundamental note can still be recognized and I can easily sing a seventh chord with it: D3-F#-A-C4, with the natural seventh, which is intoned differently than on the piano.

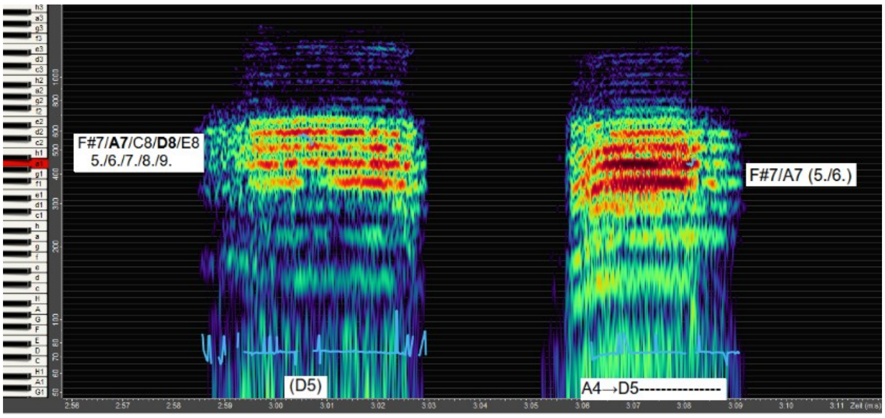
7) D5



What is interesting about this spectral sound is that it can be clearly seen in the spectrogram that it is produced by both parts of the syrinx. First Syrinx 1 begins, seen at the 1st octave A5→D6----, then Syrinx 2 joins in in full sound and continues to vibrate when Syrinx 1 ends, as can be seen at D6. So it's not a reverberation, but a real sound with the fundamental note D5 marked. This spectrogram also shows that the sound of Syrinx 2 alone is not that strong. The sound of S1 and S2 doesn't just seem twice as loud, but rather much stronger and fuller. This means that the coordinated interaction of two independent sounds leads to a *cumulative interaction* in the overall spectrum. The vibration systems of S1 and S2 with their respective spectrum structure and dynamics complement, reinforce and stimulate each other in a feedback manner so that the entire sound system reaches a higher energy level.

This D5 sound, from the "dominant" A4 to the "tonic" D5, is a spectral sound that is strongly dominated by the fundamental tone, although it only sounds very weak. This is due to the very intense third F#7 and the fifth A7. In this sound, the D major triad can naturally be heard in the 2nd octave, as is appropriate for any well-voiced and fully sung sound (in human singers).

D5 and D5 in comparison



The first D-5 sound is a veritable spectral sound with impressive timbres. When I listen, I have the impression that I am listening into a wide, deep space that is completely filled with a variety of shimmering color vibrations.

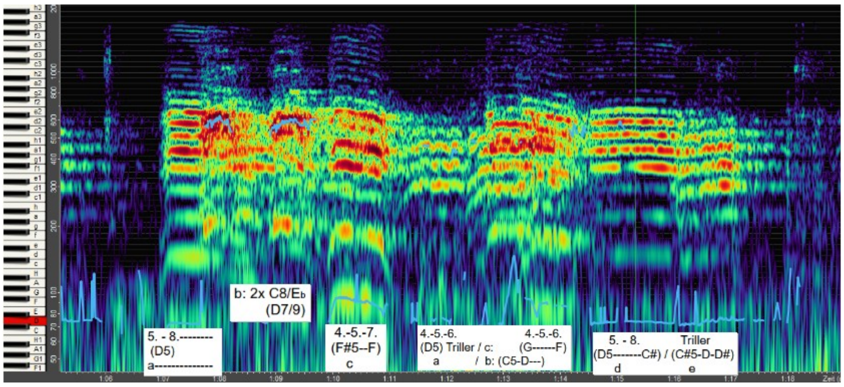
The second D-5 sound seems deeper, earthier, more sonorous to me when it comes from the depths (from the A4) and fully fills its space as a triad with the fifth and third.

next page:

8 Sequences of Spectral Sounds from several Zebra Finches

8 Sequences of Spectral Sounds from several Zebra Finches

1) six Zebra Finches in one sequence



Of course I can't say for sure which Zebra Finch sings what. I based the assignment on the type of sound figure and the intensity. The two D5 trills could also be from the same finch.
You can hear a very attractive modulation in this sound sequence: D major - (D) dim7 – F#7-F – D – G – D, although the diminished seventh chord (F#/A/C/E♭) sounds a bit noisy.

5. - 8.--------
(D5)
a--------------

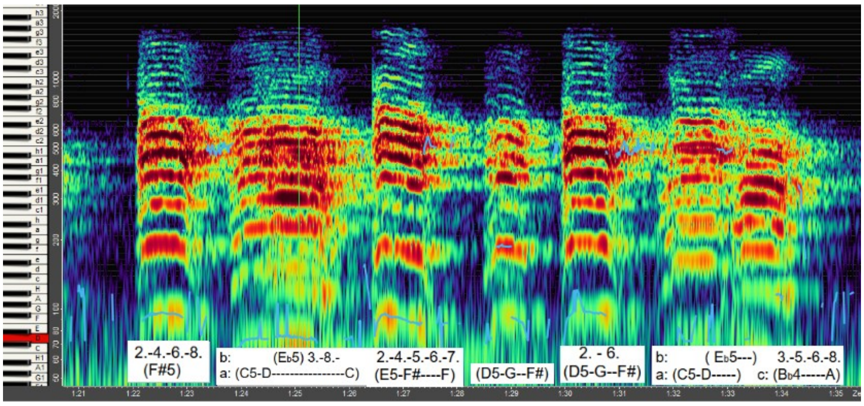
b: 2x C8/E♭
(D7/9)

4.-5.-7.
(F#5--F)
c

4.-5.-6. 4.-5.-6.
(D5) Triller / c: (G------F)
a / b: (C5-D---)

5. - 8. Triller
(D5--------C#) / (C#5-D-D#)
d e

2) nine calls



A sequence of 7 calls with the following basic tones:
F#5 – D5 – F5#-F – G5-F# - G5 – D5 – Bb4-A.
The 1st, 3rd and 5th calls appear to come from the same finch. With the 4th call, with the same pitch and sound as the 5th, you can hear how different it can sound when the spectral sound has a different structure, which is not due to the volume.
On the 2nd and 6th calls (D5) another finch sings an Eb5, which results in a little more intense rubbing sound. Maybe the birds don't even see this as a mistake, but instead have a special appeal for them.
It is interesting how the last call on the low A seems to comment on the somewhat dissonant sound of the other two finches.

2.-4.-6.-8.
(F#5)

b: (E♭5) 3.-8.-
a: (C5-D----------------C)

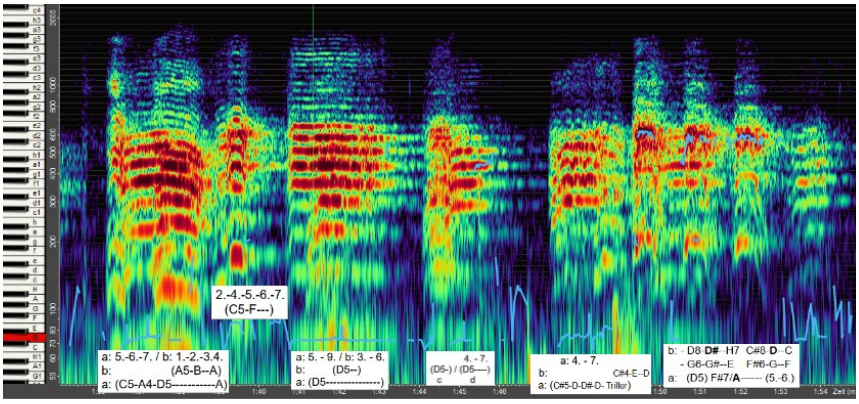
2.-4.-5.-6.-7.
(E5-F#----F)

(D5-G--F#)

2. - 6.
(D5-G--F#)

b: (E♭5---) 3.-5.-6.-8.
a: (C5-D-----) c: (B♭4-----A)

3) 12 mostly simultaneous calls



On the first call, ZFa begins with C5-A4-D5-- (5.-6.-7.), to which ZFb sings a low A-B4-A (4.-9.). The F#7 (5.) of D5 corresponds exactly to the F#7 (6.) of B4, as do A7(6.) and A7(7.).
In the third call, both finches are in the same spectrum of D5 with a difference in the distribution of partials. At ZFa are the 5.-9. strongest, with ZFb it is the 3.-6. partial tone.
At the fifth call you hear the figure C#-D-D#-D-E-D due to the interaction of 2 finches.
In the last figure, ZFa holds the A7 while ZFb produces three intense calls: D8-D#-B7 (2x) and C#8-D-C.

a: 5.-6.-7. / b: 4. - 9.
b: (A4-B--A)
a: (C5-A4-D5-----------A)

2.-4.-5.-6.-7.
(C5-F---)

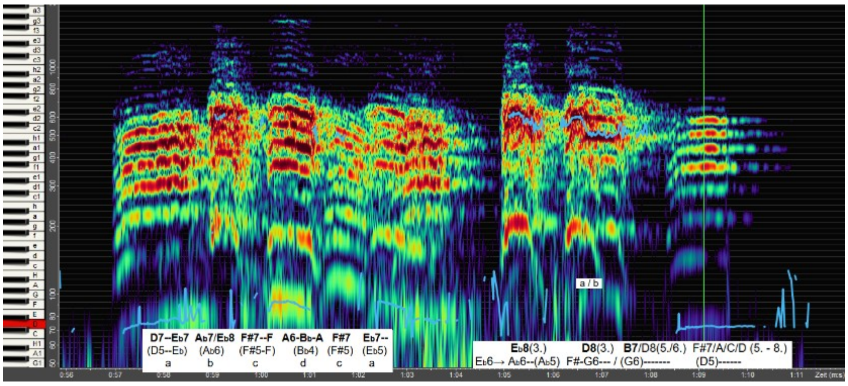
a: 5. - 9. / b: 3. - 6.
b: (D5--)
a: (D5---------------)

4. - 7.
(D5-) / (D5----)
c d

a: 4. - 7.
b: C#4-E--D
a: (C#5-D-D#-D- Triller)

b: - D8-**D#**--H7 C#8-**D**--C
- G6-G#--E F#6-G--F
a: (D5) F#7/**A**------ (5.-6.)

4) four ZF in harmonical "Conversation"



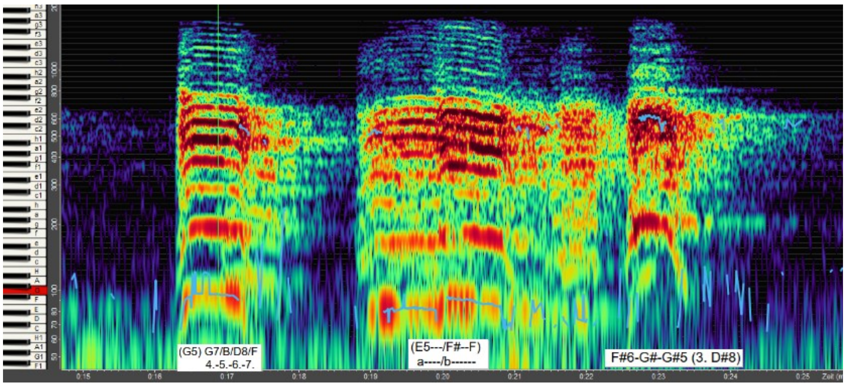
Although the core spectrum of all 4 Zebra Finches is in the same range between C7 and C8, the calls sometimes sound higher and sometimes lower because the virtual and actual fundamental tones have a different position: D5-D# – G#6 – F#5 – A4 – F#5 – D#. In the spectrogram you can clearly see how one spectrum emerges from the previous one and continues to the next.
A kind of melody is formed in the sequence of sounds: C#-D#-D#-F#-E#-A#-F#-D#. After 2 somewhat loud, noisy sounds, a nice, clear spectral sound follows with D5 as a virtual grunt tone.

D7--Eb7 **Ab7/Eb8** **F#7--F** **A6-Bb-A** **F#7** **Eb7--** **Eb8**(3.) **D8**(3.) **B7**/D8(5./6.) F#7/A/C/**D** (5. - 8.)
(D5--Eb) (Ab6) (F#5-F) (Bb4) (F#5) (Eb5) Eb6→ Ab6--(Ab5) F#-G6--- / (G6)--- (D5)---
a b c d c a

harmonic order:
Eb7 - Ab - F#7 - Bb - F#7 - Eb
basic tone sequence with Glissandi: D→Eb5--/ Gb-Ab6--Gb / F#5--→F / Bb4-→A-Ab / F#5--→F / D-Eb5---

For a detailed description and analysis of this particular sequence, see below p. 20

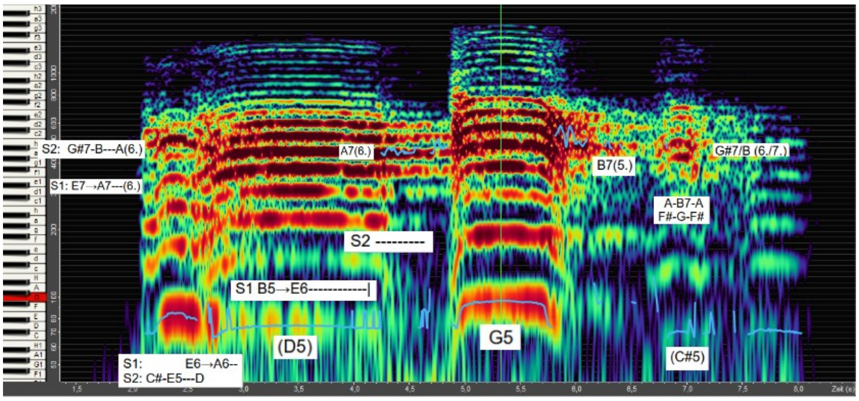
5) two Zebra Finches together E5 → F#5



1) G5 spectral sound: partials G7/B/D8/F (4.-5.-6.-7.)
2) ZFa: E5---- / ZFb: F#5—F – The spectrum of E5 (a) flows smoothly into the spectrum of F#5 (b), which can also be seen in the high spectrum G8-C#9.

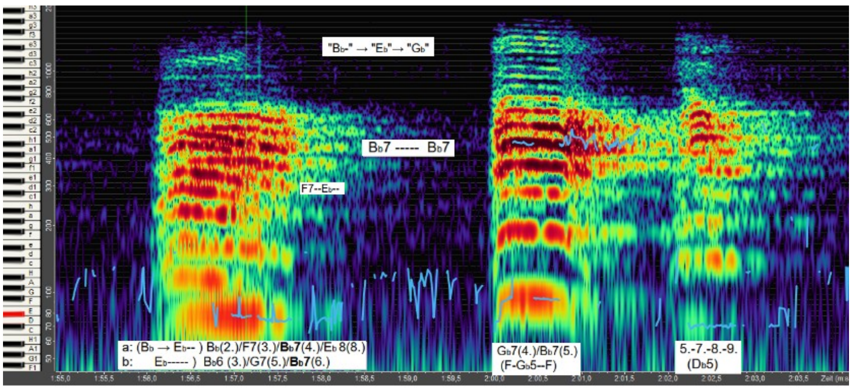
F#8(9.) → F#8(8.)
E8(8.) → E8(7.)
D8(7.) → C#8(6.)
B7(6.) → A#(5.)
a b

6) two ZF D5 / G5



ZFa: (D5)------ ZFb: G5--- : detailed analysis see “7 spectral sounds” (p. 11)

7) Modulation Bb → Eb while singing



A wonderful example of how elegantly these Zebra Finches can react to each other in the sound spectrum.
a: (Bb → Eb--) Bb(2.)/F7(3.)/**Bb7**(4.)/Eb 8(8.)
b: Eb-----) Bb6 (3.)/G7(5.)/**Bb7**(6.)

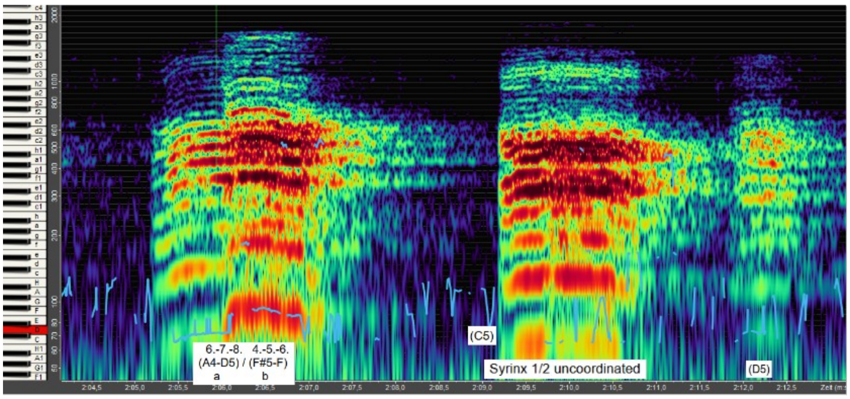
ZFa starts on a Bb4 spectral sound and then when ZFb starts with an Eb5 spectral sound, ZFa also modulates sliding into an Eb5 sound until its Bb7 as the 8th partial matches the Bb7 (6.) of ZFb.
As you can see in the spectrogram, the two fifths of the Bb4 sound clearly slide into the Eb5 sound, the F7(6.) to the Eb7(4.) and the double fifth C8(9.) to the Bb7(6.).

Gb7(4.)/Bb7(5.) 5.-7.-8.-9.
(F-Gb5--F) (Db5)

And the modulation goes even further. The next finch follows the "B flat major" and "E flat major" with the Bb7 with another very loud Bb7, which is now the intense third (5.) of Gb5 – a sophisticated modulation from "E flat major" to " G flat major", which the following finch continues after "D flat major" (fifth to G flat major).

What amazingly musical ears the Zebra Finches have!

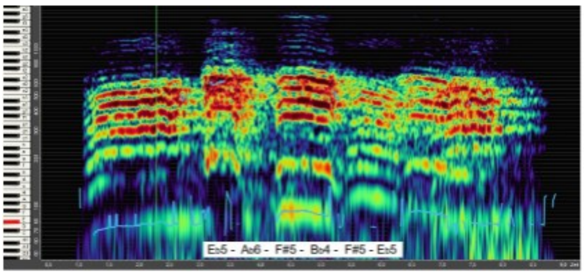
8) two ZF: successful modulation D major → F sharp major /
one ZF: failed coordination of S1 and S2



After a short break there is another musically well-known modulation into the third, from "D major" to "F sharp major", a relationship of thirds, called "mediant". The D5 and F#5 are connected via the F#7 (5./4.). ZFa also comes from "A major" (A4-D5---) and ZFb slides from F#5 to F5.

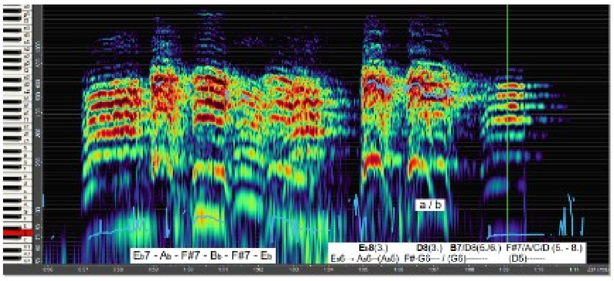
After this musically and vocally high-quality performance, a small disaster follows. The next Zebra Finch fails to coordinate both parts of the Syrinx. Syrinx 1 begins with Bb4-C5--- and 0.02 s later Syrinx 2 begins with B4, which results in a clear discord. After 0.7 s the finch starts again, but again he doesn't manage to get both membranes to oscillate in the same spectrum.
Just as the Zebra Finch was previously able to adapt to the other finches by hearing while singing (Bb to Eb), this finch hears when singing that the sound is not right and tries to start again to correct itself. We humans can also correct the intonation of a tone via our ears while singing in less than 0.5 s.

Analysis of Sequence 4 - four ZF in harmonical "Conversation"



4 Zebra Finches sing 6 spectral sounds in this sequence: Eb7 - Ab - F#7 - Bb - F#7 - Eb.
The first and last sound is probably sung by the same finch as well as the two F#7s by another finch.
All sounds have a slight glissando movement in the fundamental tones: D5→Eb- / Gb-Ab--Gb / F#--→F / Bb4-→A-Ab / F#5--→F / D-Eb---.

The first sound is actually a seventh chord made up of the partials Eb7/G/Bb/Db8 (4.-7.) with the virtual fundamental at Eb5. The sound starts at C#/D5 glides to Eb5 and develops a strong vibrato. Another Fink reacts to this with the “lower fifth” Ab5 (6.-Eb8 = 8.- Eb5), a strong noisy sound. This is followed by another seventh chord, F#5 (4.-7.), which slowly slides a semitone lower to F5. All 3 sounds move in the same spectrum, but then from the fourth finch comes a sound with the virtual fundamental note Bb 4, which sounds significantly lower than the others and slides even lower to Ab4. Then the 3rd Fink comes again with his slightly quieter F#5, into which the 1st Fink again sounds his Eb5 with a moving figure in the upper voice: C8-C#-C-B7-Bb.
The harmonic order of this sequence can be analyzed as follows: fifth relationship E flat major - A flat major / (A flat major = G sharp major) from G sharp major to the double subdominant F#7 and then not to B major, but to the upper mediant A# major (= Bb major) / back to F#7 and further into the lower mediant D# = E flat major. This could well be the idea of a 19th century composer.



The complete sequence
After the 6 spectral sounds, the 2nd finch appears again with two intense sounds Eb8 (3. of Ab6) and D8 (3. of G6). And there is another Fink in precise intonation with B7, the third of G6. The conclusion of this sequence is a 6th (?) Fink with a strangely low D5, after "G major" so "D major".

Eb8(3.) **D8**(3.) **B7**/D8(5./6.) F#7/A/C/D (5. - 8.)
Eb6→ Ab6--(Ab5) F#-G6--- / (G6)------- (D5)------

The entire fundamental tone sequence is: Eb5 - Ab6 - F#5 - Bb4 - F#5 - Eb5 - Ab6- G6/G6 - D5

In the sequence of the spectral sounds, the modulation cannot naturally be heard as clearly or pure, on the one hand because the spectral sounds always have a slightly noisy quality to our ears due to the density of the partial frequencies, and on the other hand because the sounds of the birds are always in motion, in the semitone Glissandi, in smaller up or down movements or in a stronger vibrato. They are extremely lively vocalizations that express a vegetative state of excitement (Vagus nerve→Syrinx) and at the same time have a stimulating effect on the basic vegetative excitation via the hearing (ear→syrinx→vagus nerve). This process of interaction applies to the ear/syrinx/vagus nerve system in each individual bird, to the effect from bird to bird, and to the acoustic field and arousal level of the entire group.

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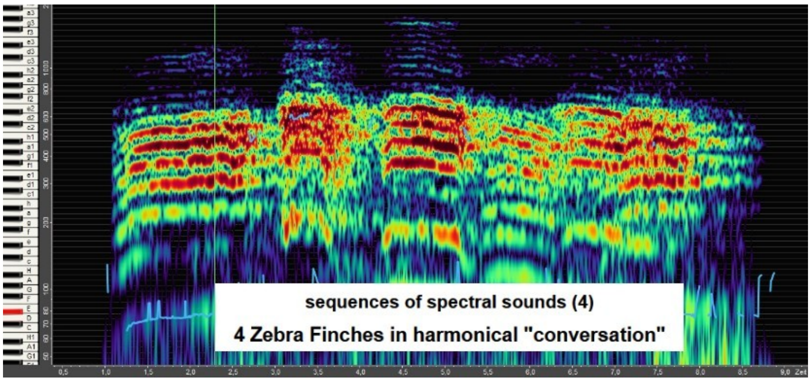
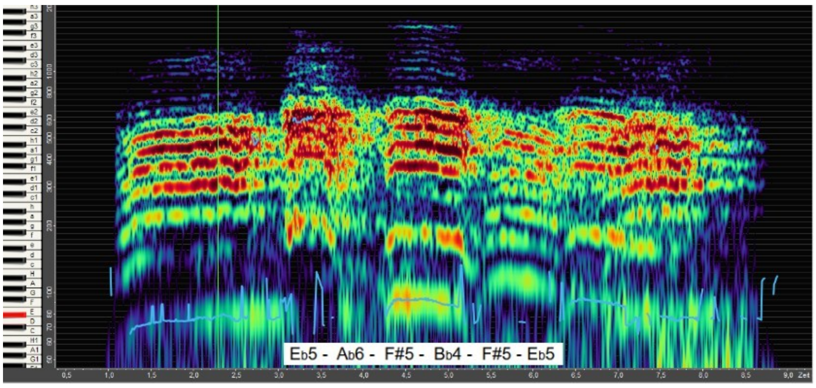
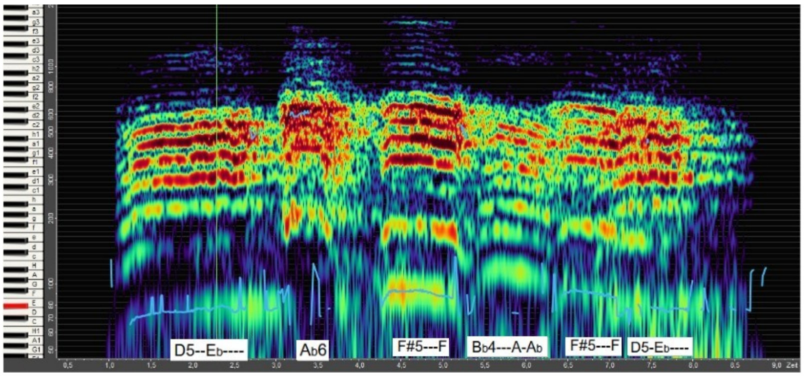
all spectrograms for sequence 4: four ZF in harmonical "conversation"

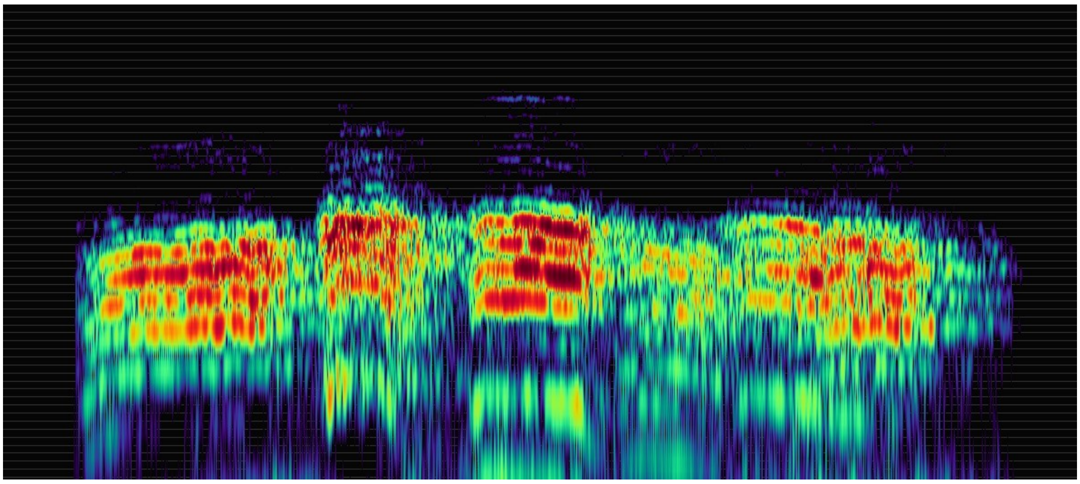


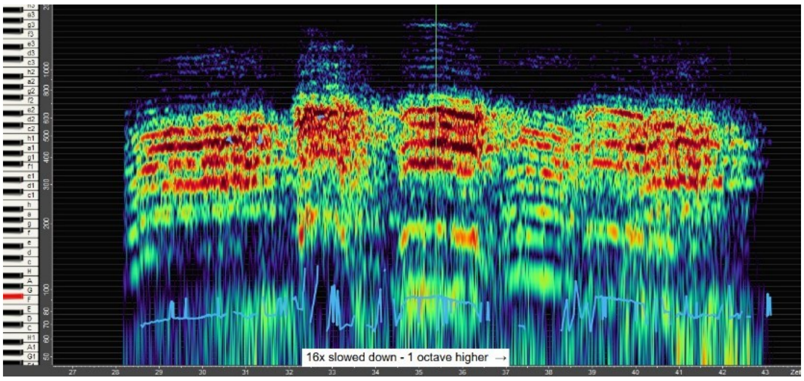


virtual fundamentals

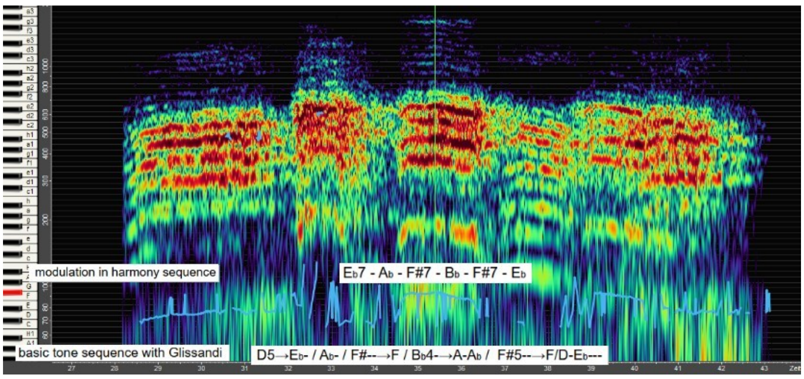


fundamentals with glissando

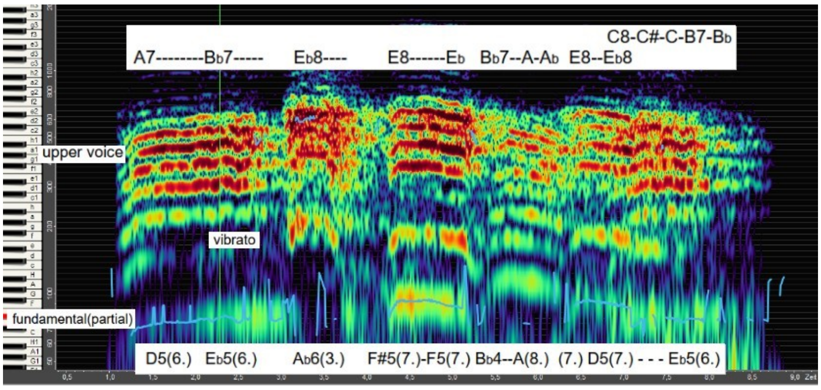

slowed down 16x



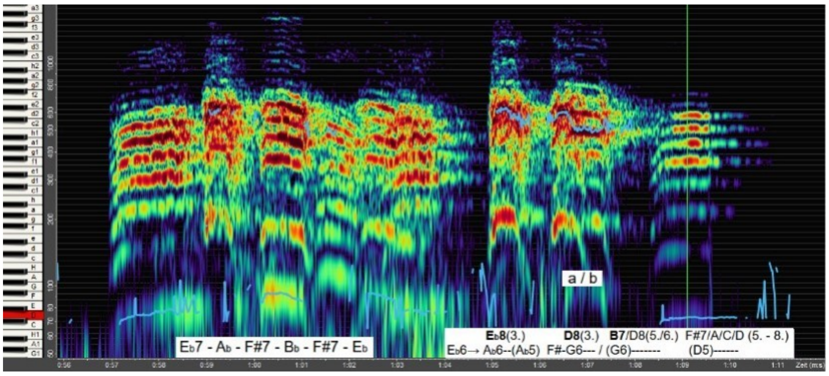
16x slowed down - 1 octave higher



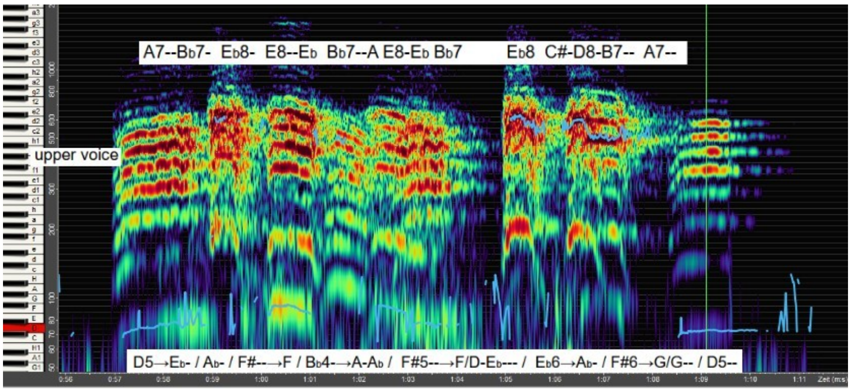
modulation in the harmony and fundamental sequence



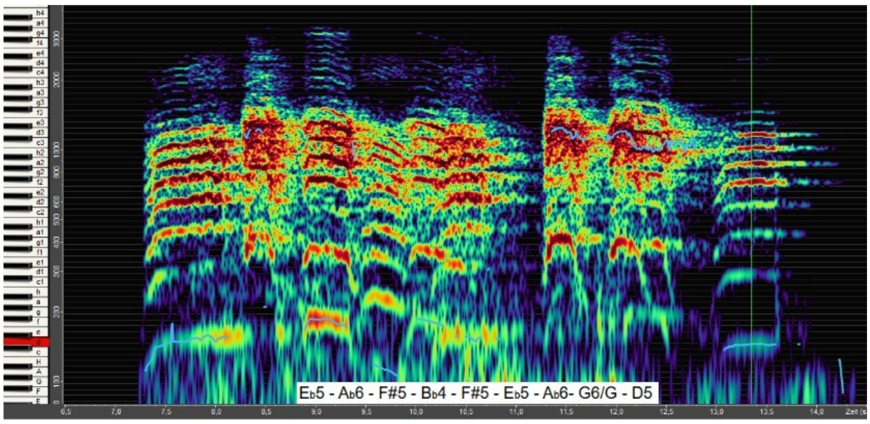
"upper voice" and 1st partial tone (fundamental tone)



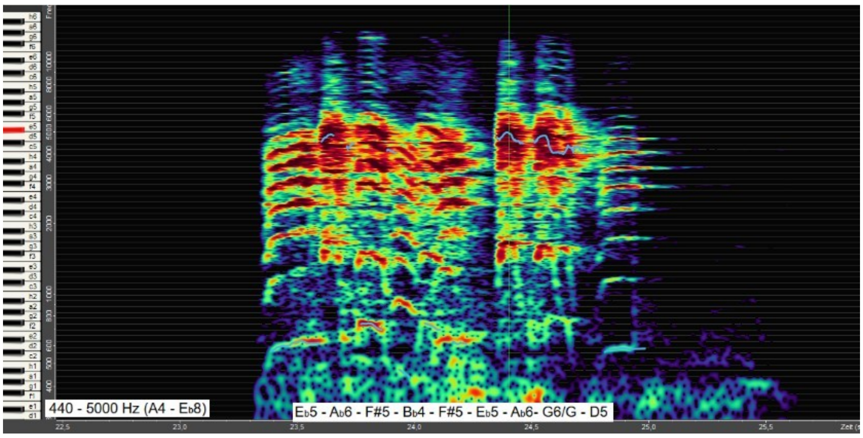
the complete sequence



"upper voice" and virtual fundamentals



4-fold slowed down



original at 440 - 5000 Hz (A4 - Eb8)