Luka Aron

Phainesthai
Auditory Processes as Tools for Musical Composition

Skriftlig reflektion inom självständigt arbete
Till dokumentationen hör även följande inspelning:

XV XXVII III XXI IX: Variations

“Phainesthai” (φαίνεσθαι): “to appear”
ABSTRACT

The human auditory system can become an active agent in the production of sound when stimulated with specific tone combinations. The resulting auditory distortion products can be amplified and drawn attention to by employing certain just intonation practices – a compositional technique that may serve as a powerful catalyst for reaching different states of mind in listeners.

In this thesis, those psychoacoustic phenomena critical to the act of tuning are explored. An experiential tuning protocol is introduced and supported by insights from physiology and neuroscience research. Based on the tuneability of musical intervals, a harmonic framework involving harmonic and subharmonic relationships is analyzed and exemplified via the accompanying composition XV XXVII III XXI IX: Variations.

From a phenomenological perspective, the research extends to broader contexts, investigating potential social, ethical, cultural, and political implications of such a practice.

Keywords: music, psychoacoustics, auditory distortion products, tuning, just intonation, phenomenology
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INTRODUCTION

In this thesis, a method for musical composition based on the observation of acoustic and psychoacoustic phenomena is explored. The focus lies primarily on certain auditory distortion products, such as combination tones, and how they relate to the use of just intonation. An experiential tuning protocol is introduced and backed by insights obtained from investigations in the fields of physiology and neuroscience.

Through a phenomenological perspective, the research is placed in a broader context by investigating possible social, ethical, cultural, and political implications of such a practice.

The practical work accompanying this thesis is XV XXVII III XXI IX: Variations, a composition for Buchla 200, bass clarinet, contrabass, euphonium, foghorn organ, harpsichord, serpent, shō, and trumpet. In this piece, certain compositional techniques through which our auditory system can become an active agent in the production of sound are incorporated. Due to the nonlinearity of the inner ear, additional tones can be produced by our auditory system, depending on which set of primary tones is presented to the listener, offering great creative potential while challenging the general assumption of our ears as merely passive receivers.

Following extensive testing of the tuneability of musical intervals, a harmonic framework involving multiple closely related harmonic series, whose fundamentals are based on the subharmonic series, was developed. It is an almost self-generating system, where the harmonic domain of the compositions follows the path of least resistance (as will be outlined later), with some minor algorithmic interventions set beforehand. Out of this discovery came forth the motivation of developing a compositional practice where one’s perception is not the endpoint but rather the beginning – or where nature serves as a directive, and the composer’s task is merely to uncover or zoom in on something that is already there.

The text will be divided into four sections. First, the philosophical underpinning of this practice is examined, with an emphasis on phenomenology. Next, the physiological processes supporting the sensation and perception of sound will be outlined. Here, relevant information that could be useful for composers will be illuminated. This section is closely tied to the specific psychoacoustic phenomena utilized in the accompanying piece XV XXVII III XXI IX: Variations, and their underlying mechanisms will be explained.

Lastly, an introduction to the practice of tuning and the principles of just intonation are provided, accompanied by a specific harmonic framework developed through the observation of the tuneability of musical intervals.

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PHENOMENOLOGICAL APPROACHES TO LISTENING

Part of the motivation behind this text is to develop a compositional method in which our experience of sound serves as the primary influence – a practice based on the observation of the sensation of sound, where the composer’s task is to merely uncover something that is already there, making the listener a witness to natural phenomena.

This approach is related to the ancient Greek concept of phainesthai (φαίνεσθαι), which pertains to the way in which things appear to us, as opposed to their objective existence.³ Similarly, this practice involves an empirical approach to sound production and perception, whereby the focus is on the observation and analysis of the perceptual qualities of sound, rather than on preconceived ideas or beliefs about its symbolic meaning or function.

In this regard, this practice is also related to phenomenology, the study of the human experience of things in the world, which cannot only be achieved by means of language or the understanding of symbols but by “[...] go[ing] back to the things ‘themselves,’” with the approach of “a perpetual beginner.”⁴

Understanding the human experience as a relationship between phenomena, many phenomenologists, such as Heidegger and Merleau-Ponty, proposed an alternative to Descartes’ dualism of subject and object. As there is an infinite number of things to apprehend, we scale our perception to a very constrained subset of those things, making the world we live in inherently self-defined. This perceptual frame (which Heidegger called Dasein)⁵ is the “being there,” with you at the center of your realm of experience. In other words, without a subject, nothing at all would exist to confront objects – but this object is not something that is easily reducible to a single set of properties, as it is shaped by our experience of it. The Swiss psychiatrist Binswanger argues that “what we perceive are ‘first and foremost’ not impressions of taste, tone, smell or touch, not even things or objects, but meanings.”⁶

No different from other branches of philosophy, most phenomenologists have focused on vision as the primary sense through which we experience the world. However, several thinkers have approached the topic through the perspective of listening, one of them being Jean-Luc Nancy, who questions why, in philosophy, we give preference to the visual as making something evident or to perceive meaning, while the audible is often subordinated.⁷

In his writings, Maurice Merleau-Ponty explored the interconnection between the body and perception and its effects on our experience of the world.⁸ He states that music has a unique

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⁷ J. L. Nancy, Listening, p. 2.
⁸ Merleau-Ponty, Phenomenology of Perception, pp. 402-403.
capability to express the “lived body” and its relationship with the environment. Merleau-Ponty argued that music is not a representation of the world, but rather a presentation of it, offering a distinct mode of experiencing the world through sound. This connection is facilitated by music’s ability to express the pre-reflective and unconscious aspects of our experience, which are not accessible through language or other forms of representation. As such, it can be said that music is always inherently an approach to the self, as the sound waves quite literally put our “body-subject” in resonance, which might serve as an explanation for the deeper meanings we often obtain from it.

In his thought-provoking manifesto The Music to Come, François Bonnet posits that “[…] music remains to be discovered,” that it is “still hidden” and takes this statement even further by saying that “[…] all musics produced up until now have been nothing but simulacra, rituals to call music forth.” While such a claim may seem outrageous to some and challenge what we hold as fundamental and essential, it is rooted in the observation that much of music as we know it is heavily influenced by various extra-musical cues, including concepts, systems, visual analogies, and particularly, language. This is evident in the terminology around the description of music, with common expressions borrowed from linguistics, such as “musical vocabulary,” “call and response,” “musical phrasing,” “storytelling,” among many more. Even the use of a standardized notation system indicates a linguistic line of thinking. Furthermore, metaphors are commonly used in the discourse about sound, most prominently the description of pitch with height properties, such as low and high, or the common description of a minor scale being sad and a major scale being happy. I would argue that such an approach cannot be called a phenomenological one. A musical practice informed by phenomenology must begin with an “as naïve and full a description of direct experience as possible.”

In the same vein, the composer Chiyoko Szlavnic talks about her work: “The absence of a mediatory symbolic language […] right at the beginning of the process allows me to create music which itself is, I hope, unburdened by historical signification, tradition, ideology—or expectation” – a lofty, perhaps impossible aim, as our understanding of the world is inevitably shaped by our personal experiences and cultural background. But just as the word music will always fleet any definition, nothing contained in what we call music is ever an absolute truth. However, one can observe and define tendencies, both in the way one listens, as well as in how

9 Merleau-Ponty, Phenomenology of Perception, pp. 77-88.
11 Merleau-Ponty, Phenomenology of Perception, pp. 87-106.
13 It is interesting to note that this will vary in different cultures: musicians from Bali and Java use the metaphor of size (small and large), while some cultures in the Amazon use the terms young and old.
one constructs and organizes sound. Therefore, Szlavnic’s aim holds valid, as long as it is not turned into an ideology and no superiority to other ways of approaching music is implied.

Music is often talked about as a “universal language” – even Marcel Proust wondered “[…] whether music were not the sole example of the form which might have served–had languages, the forms of words, the possibility of analyzing ideas, never been invented–for the communication of souls.”16 Although one may suggest that this “communication of souls” may have a more universal quality through music than through language – the latter being often influenced by one’s origin and territorial designation – it remains undeniable that the experience of music is significantly shaped by socio-cultural conditioning. Moreover, besides aspects of enculturation, many other extramusical factors contribute to listening being a profoundly subjective experience. Studies have found that there are large individual differences in the perception of, for example, certain auditory illusions (such as the tritone paradox),17 determined by one’s own speaking voice and the language (or even dialect) one has been primarily exposed to during early childhood years. Differences have also been observed between right- and left-handers.18

And while cultural and regional differences contribute to the richness of the musical landscape, the cultural hegemony of Western classical music has been held up as a universal standard of musical sophistication for a long time. Through this, the perception and representation of other musical traditions are negatively affected, and colonial structures are reinforced.19 It is a prime example of how music can be abused to serve the power dynamics at play on a global scale.

As a counteract, when applying the mindset of a “perpetual beginner” to the realms of music and returning to “the things themselves” (as mentioned above), one could adapt Bonnet’s suggestion of approaching music as “driven by experience and by the phenomenon of sound”20 – a strategy that is fundamental to the act of tuning, as will be outlined on page 14.

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THE PHYSIOLOGY OF HEARING

The following section aims to provide a foundational understanding of the mechanisms behind our sense of hearing. By exploring the biomechanics of hearing, this section will delve into the intricate workings of our auditory system and highlight key factors that may be of interest to composers looking to work with psychoacoustic phenomena.

When airborne sound enters a human’s ear, it first hits the pinna (also known as the auricle), which is the only visible part of our hearing system, shaped like a helix and functioning as a funnel – collecting, filtering, and directing sound waves towards the auditory canal where their pressure brings the tympanic membrane (or eardrum) into movement. Those vibrations are then conducted to the cochlea (the inner ear) via the ossicular system of the middle ear. The fluid-filled and spiral-shaped cochlea also contains the Organ of Corti, where the vibrations are transformed into electrical energy by the inner hair cells and finally transmitted to the auditory brainstem through the auditory nerve.

![Classic coronal illustration of the ear by Max Brödel (1939)](image)

*Figure 1. Classic coronal illustration of the ear by Max Brödel (1939)*

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As one would expect from such a multi-staged process, some properties of the sound, as it exists in the world outside of us, will not remain unchanged after entering our organism. Put differently, in course of evolution, different species have developed to extract the auditory information necessary for their survival. In the case of humans, the ordinarily perceptible frequency range is 20 Hz to 20’000 Hz in a young and healthy individual. It is important to note, however, that this full range can only be achieved by intense sound pressure levels; at 60 dB, the range is only approximately 500 Hz to 5’000 Hz. Furthermore, our auditory system acts as a compressor, vastly reducing the dynamic range of the incoming sound by a factor of approximately 100 million, thereby facilitating the discernment of sounds spanning a wide range of amplitudes, from the faintest rustle to intense sonic bursts, while maintaining our ability to perceive and process these auditory stimuli with remarkable sensitivity.

To be able to estimate the location of a sound source on the horizontal axis, our brain makes sense of both the difference in intensity and timing of the sound entering one ear, then the opposite. Complimenting this mechanism, the pinna is performing the function of a reflective surface, aiding to locate the sound source in the three-dimensional space. It can thus be said that our auditory system has a nonlinear response to external stimuli, a behavior that can especially be observed in our inner ear. This non-linearity leads to a plethora of artifacts, and the underlying mechanisms, as well as creative possibilities of some of these psychoacoustic phenomena will be the subject of the next section.

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Combination Tones

Combination tones are faint sounds that, under certain conditions, are perceived by the listener as a result of presenting the auditory system with two (or more) stimulus tones. They are not present in the original sound waves but occur due to the nonlinearity of the inner ear, being created along the basilar membrane in the cochlea.\(^{24}\)

In musical literature, they are commonly referred to as *Tartini tones*, named after the 18th-century Italian composer and violinist Giuseppe Tartini, who is credited with their first discovery. Later, Hermann von Helmholtz investigated their underlying mechanisms and described them as “mechanical tingling in the ears.”\(^{25}\) More recently, several composers and sound artists such as Thomas Ankersmit, Jacob Kirkegaard, Phil Niblock, and Maryanne Amacher have employed them in their compositions, the latter referring to them as ‘ear tones’ or ‘ghost tones.’\(^{26}\)

In the clinical context, they are known as distortion product otoacoustic emissions (DPOAEs) and are used to assess cochlear functioning, a diagnostic tool particularly useful in newborns.\(^{27}\)

There is a multitude of distortion products, but the most commonly perceived are the quadratic difference tone (QDT) and the cubic difference tone (CDT), which occur at the frequencies of \(f_2 - f_1\) and \(2f_1 - f_2\), respectively. There are also other difference tones that occur at other arithmetic combinations and higher orders – such as summation tones \((f_1 + f_2)\) – but these are less audible and are therefore not discussed in this text.

Several factors can affect the perceptibility of difference tones, including overall amplitude, frequency range, and timbre. In addition, the intervallic relationship of the stimulus tones plays a critical role, with narrower intervals (within an octave) generally producing more audible difference tones than wider intervals (extending the octave). However, concluding from my own empirical tests, frequency ratios below 1.125 and above approximately 1.875 do not produce discernible additional tones – findings that were later confirmed by a study conducted by Alex Chechile, which looked at the perception of difference tones in two and three-tone stimuli.\(^{28}\) In clinical settings, a range of frequency ratios between 1.19 and 1.26 has been

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reported to elicit maximal DPOAE levels,\textsuperscript{29} which closely aligns with my own observation of a frequency ratio of 1.16 (7/6) as the most effective in evoking the perception of difference tones.

**Achieving a sense of spatiality through difference tones**

Through the usage of difference tones, another spatial layer is added to the experience of the music, as the sounds present in the room merge with the sounds emitted by the listener’s ears. Maryanne Amacher describes the motivation behind employing this phenomenon in her composition *Perceptual Geography* as:

“seek[ing] ways of composing in which tones, originating within human anatomy, exist in their own right by becoming perceptually more than an accident of acoustic tones in the room, resulting in a conscious interplay between them. [...] The object of perceptual geography is to learn to compose spatial dimensions in music – the kind of aural dimension we experience in life, but usually not in music. The idea is to create a world for the audience to enter where architecture magnifies the expressive dimensions of the music. In this approach, the phrases of the music are choreographed to sound at specific heights and locations. Tactile in presence, they appear both larger than life and small enough to touch, heard as though miles away, or felt inside the listener.”\textsuperscript{30, 31}

The quality of such auditory distortion products changes drastically, depending on the position of one’s head, offering a direct interaction with the sound in the physical space. Swedish composer Ellen Arkbro has taken advantage of this interaction in her radiophonic piece *Selected Collections*, which encourages listeners to move freely within the space in which the piece is played, thus creating an interaction between the room’s “sonic architecture” and the listener’s “body [...] and listening mind.”\textsuperscript{32} This concept aligns with the ideas put forth by philosopher Merleau-Ponty, who emphasizes the importance of the “body’s spatiality and motility.”\textsuperscript{33}

Being purely monophonic, the piece’s spatialization is primarily dependent on the listener’s movement and, thus, their “embodied attention.” The use of phase-locked sawtooth wave chords in extended duration serves to amplify this effect, allowing for the exploration of various acoustic and auditory artifacts, including standing waves, phase relationships, and


\textsuperscript{31} To experience difference tones and their spatial aspect, listening to Amacher’s piece ‘Sound Characters (Making the Third Ear)’ on speakers (rather than headphones) is recommended. A recording can be found here: https://vimeo.com/88559973. [Accessed April 12, 2023].

\textsuperscript{32} Arkbro, Ellen, "@ellenarkbro," Twitter, February 1, 2020, 8:35 AM, https://twitter.com/ellenarkbro/status/12210530303372302656.

combination tones. As Arkbro notes, “Different listeners will hear different things, at times radically different.”

**Missing fundamental phenomenon**

Difference tones are often confused with the missing fundamental effect, a similar phenomenon where the brain *fills in* a fundamental frequency that is not present in a complex sound whose frequency components are integer multiples of that missing fundamental. For example, if a sound is composed of the harmonics at frequencies 200 Hz, 300 Hz, 400 Hz, and so on, the brain may perceive the sound as having a fundamental frequency of 100 Hz, even though this frequency is not actually present in the sound (*Sound File 1*). Although both difference tones and the missing fundamental effect involve the perception of frequencies that are not present in the original sound, they are based on different mechanisms. As discussed previously, difference tones result from the nonlinear distortion of the ear’s basilar membrane, whereas the missing fundamental effect (also known as periodicity pitch, residue pitch, or virtual pitch) arises from neurological processes related to the brain’s ability to recognize the periodicity in a complex sound.\(^{34}\) Other neural mechanisms that may be involved include phase locking of neural firing to the sound waveform, as well as the processing of temporal cues such as the rate and pattern of firing of neurons in the auditory nerve. However, although studies have shown that these phenomena are distinct, they are known to reinforce each other.\(^{35}\)

**Intermodulation Distortion Products**

To a varying degree, nonlinearities can also be found in most audio equipment, resulting in Intermodulation Distortion (IMD),\(^{36}\) otherwise known as harmonic distortion. Occurring when two or more signals are combined, a nonlinear circuit (speaker, amplifier, etc.) will produce additional sideband frequency components at both the sum and difference of its input, following the same mathematical order as combination tones.

To demonstrate this, *Figure 2* illustrates two sine waves at 513.\(^{\frac{1}{3}}\) Hz and 440 Hz, forming a 7/6 interval. As can be seen in *Figure 3*, when processed by a Soundtoys Decapitator distortion plugin, both sum and difference tones are added. Due to the intensity of the distortion, a near-infinite number of additional harmonic partials at other arithmetic combinations and higher orders is produced, locating the 7/6 interval as occurring between the 6\(^{\text{th}}\) and 7\(^{\text{th}}\) partial of a harmonic series, in this case with a fundamental frequency of 73.\(^{\frac{1}{3}}\) Hz. In the accompanying *Sound File 2*, the distortion is gradually introduced, demonstrating a transition from pure sine tones to distorted signal.

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\(^{36}\) Despite not being a psychoacoustic phenomenon, Intermodulation Distortion Products are included in this section due to their close relation to combination tones.
Figure 2. A pair of sine waves in a 7/6 relationship (440 Hz + 513.3 Hz)

Figure 3. A pair of sine waves in a 7/6 relationship (440 Hz + 513.3 Hz), processed by a Soundtoys Decapitator plugin

IMD is usually considered undesirable and thus attempted to be minimized in the engineering process of audio equipment. For example, the quality of a speaker system is largely determined by its linear frequency response, referring to the ability of the circuit to produce an equal output level at all frequencies within a specified bandwidth for an equal input level.

There are cases, though, where harmonic distortion is desired, for example, in the case of subtle saturation processes in the mastering stage of music production, in order to add harmonics to a signal, resulting in a richer and more alive sound. IMD can also be used creatively in a similar way as combination tones. My piece BEND SINISTER employs a gradual shift from combination tones to IMD, per the program note:

BEND SINISTER (2022) is a work for justly tuned Buchla 200 synthesizer tones and analog distortion units. […] A careful selection of partials is presented, stimulating additional tones in the perception of the listener, making use of a psychoacoustic phenomenon, commonly referred to as otoacoustic emissions (DPOAEs), or combination tones. Heavy harmonic distortion is then applied to the source signal, allowing the combination tones to materialize in the physical space. Through this, a secondary structure (that, in fact, exposes the subharmonic series) is gradually unveiled: like light rays meeting the surface of water, partially reflecting back to air, and refracting at once as they pass from one medium to the other.
The Critical Band

The ability to distinguish two (or more) simultaneously presented tones as separate perceptual units diminishes or disappears as their frequencies become closer to equal and cross a certain threshold. This is because the ear does not process all frequencies with equal sensitivity but instead groups them into distinct frequency bands. When sound waves enter the cochlea, they stimulate hair cells arranged along the basilar membrane. The basilar membrane is inherently fine-tuned to respond to different frequencies at different locations of the membrane, meaning that different regions of the basilar membrane are sensitive to different frequencies of sound. This creates a frequency selectivity that results in the critical band phenomenon, where frequencies close to each other activate overlapping regions, leading to the perception of those frequencies as being fused together. The width of the critical band varies with frequency, with a narrower band for higher frequencies and a wider band for lower frequencies. One composer using the critical band as a compositional tool was James Tenney, most notably in his piece Critical Band, which explores the perceptual limits of the human ear by presenting a series of ascending and descending tones that gradually become closer and closer in frequency until they are indistinguishable from one another. In this piece, Tenney’s work was influenced by the German physicist and musicologist Hermann von Helmholtz who first proposed the concept of the critical band in the mid-19th century and was instrumental in developing many theories related to the physics of sound and the perception of musical tones.

The critical band plays a crucial role in the act of tuning (as discussed in the next section), as its differential threshold defines the smallest tuneable musical interval in a given frequency range.

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37 Moore, An Introduction to the Psychology of Hearing, p. 67.

38 Link to an ensemble recording of Tenney’s piece “Critical Band” (including the score): https://www.youtube.com/watch?v=_t6vLEz725s

THE ACT OF TUNING

Across musical cultures, the act of tuning plays an important role – an iconic experience, often signaling the beginning of a musical performance about to unfold. It is a ritual of preparation and focus that requires attentive listening while in direct communion with the physical properties of sound. In the words of Dhrupad musician and researcher Sumitra Ranganathan, tuning is “[…] a way of attending the environment in ways that emphasize the sonic as a primary way of knowing,” as well as a “[…] routine that tunes the sensorium and sets the mind.”40 As such, it plays a crucial part in bringing the individual musicians of an ensemble together into a whole.

In the case of North Indian classical music, the tuning process is acted out in front of the audience, beginning with tuning the tanpura’s 2nd and 3rd strings to sa (the tonic of the raga), followed by tuning the instrument’s 4th string to sa one octave below, and concluding with tuning its 1st string to pa, a perfect fifth above the 4th string. Using the tanpura as a base reference, all other instruments are then tuned in relation to the drone instrument.41

When a symphonic orchestra tunes, it does so by relating each of its instruments to one leading instrument, traditionally the principal oboe. This leading instrument has priorly been tuned to either a tuning fork or with the help of an electronic tuner and is providing a single tone of fixed frequency (for example, A = 440 Hz)42 that the members of the orchestra are then trying to match. While instruments of similar range will adjust their tuning towards a perfect unison, other (lower) instruments will tune one (or more) octave(s) below the leading instrument. In the case of a string quartet, after matching the leading instrument, the open strings will be tuned in perfect fifths.43 Similarly, a guitar player might tune their instrument by comparing the pitch of an open string to the pitch of a fretted tone of the same frequency on an adjacent string, attempting to make them sound the same.

The perceptual method for tuning a musical interval by ear is to listen for the absence of beats, strongly audible combination tones, and the “periodicity of the composite sound.”44 When approaching a tuneable interval, the beating will gradually slow down, until disappearing completely, and qualities such as smoothness, congruency, and spectral fusion45 will become apparent (as demonstrated in Sound File 2). In the tuning protocols outlined above, musicians

40 S. Ranganathan, Dwelling in my Voice: Tradition as musical judgment and aesthetic sense in North Indian classical Dhrupad, Dissertation, 2015, p. 93.

41 Visit https://www.tosslevy.nl/tanpura/tuning-the-tanpura/tanpura-tuning-variations/ for a more detailed explanation of the process of tuning the tanpura. [Accessed April 10, 2023]

42 Reference pitches have varied over the centuries, with the standard pitch ranging from around 415 Hz to 460 Hz, depending on the time period, geographic location, and musical context.

43 In other tuning protocols, the fifths are slightly flattened to compensate for the “Pythagorean comma” occurring between the cello’s open C string and the violin’s open E string, a practice which is also called “tempering.”

44 M. Sabat and R. Hayward, Towards an expanded definition of consonance: Tuneable intervals on horn, tuba and trombone, 2006, p. 4.
make use of a set of musical intervals which Marc Sabat calls *tuneable intervals*. According to the Canadian composer and music theorist, a tuneable musical interval is one “which may be tuned precisely by ear,” suggesting a phenomenological approach to consonance and dissonance, the latter being any pitch combination that cannot be tuned by ear. He acknowledges the fact that this largely depends on the experience of the listener, as well as the “relative volume and timbre of the sounds.”

As an example, when listening to a pair of stable sawtooth waves in a 201:100 (884.4 Hz + 440 Hz) relationship (*Sound File 4*), one can observe a beating at the speed of 4.4 Hz, resulting in a certain roughness and chorus-like effect. Note that the non-periodicity of the composite sound can also be observed in the visualization of the waveform (illustrated in *Figure 4*). In the case of a pair of stable sawtooth waves in a 200:100 (880 Hz + 440 Hz) relationship (*Sound File 5*), however, there is no beating, and the two tones fuse into one perceptual unit, both audibly and visibly (see *Figure 5*).

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*Figure 4. Composite waveform of a 201/100 (884.4 Hz + 440 Hz) relationship.*

*Figure 5. Composite waveform of a 200/100 (880 Hz + 440 Hz) relationship.*

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45 Spectral fusion is a phenomenon where separate tones are perceived as one unit, occurring when the spectral components closely resemble those of a harmonic series.


47 Sabat and Hayward, *Towards an expanded definition of consonance*, p. 3.
This comparison makes apparent that, besides the unison, there appears to be a clear perceptual difference between the musical interval of an octave (here with a frequency ratio of 200:100) and nearby musical intervals, such as 201:100 or 199:100. While the quality of the octave can be described as smooth, fused, and beatless, other nearby non-harmonic musical intervals (or those found relatively high up the harmonic series, like 201:100 or 199:100) can be described as rough, separate, and beating. Besides the unison and octave, there exist several other intervals exhibiting similar perceptual qualities, such as the perfect fifth (Sound File 6), perfect fourth (Sound File 7), just major third (Sound File 8), among many others. A more comprehensive list is provided in the next section.

**XV XXVII III XXI IX: Variations – Tuning Preparation**

One experiential tuning approach that was often adhered to in the preparation of *XV XXVII III XXI IX: Variations* is to determine all tuneable intervals in a given setting. This setting, comprised of the desired instrumentation, frequency range, amplitude, etc., is determined first, followed by extensive testing. The resulting list of frequency relationships serves as the base material from which the piece is constructed. In a preliminary test, to search for tuneable intervals, two saw wave oscillators were used. One oscillator was fixed at a fundamental frequency of 440 Hz, while the other was manually swept from 440 Hz to 880 Hz, using a simple SuperCollider code, further exemplified in Video File 1. Table 1 lists all tuneable frequencies that could be determined in this particular setting. The first column lists the observed frequency values in Hz, rounded to their respective closest integer ratio (defining 440 Hz as 1/1) in the second column.

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<th>Observation point in Hz</th>
<th>Closest integer ratio</th>
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<td>537.735</td>
<td>11/9</td>
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</tbody>
</table>

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48 SuperCollider is a free and open-source programming language for audio synthesis and algorithmic composition. For more information, visit [https://supercollider.github.io/](https://supercollider.github.io/) [Accessed April 1, 2023]

49 The video demonstration is limited to the range from 1/1 (440 Hz) to 3/2 (660 Hz),
Table 1. Tunable frequencies using stable sawtooth waves

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<th>Observation point in Hz</th>
<th>Closest integer ratio</th>
</tr>
</thead>
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<td>488.8</td>
<td>10/9</td>
</tr>
<tr>
<td>495.012</td>
<td>9/8</td>
</tr>
<tr>
<td>502.8</td>
<td>8/7</td>
</tr>
<tr>
<td>513.3</td>
<td>7/6</td>
</tr>
<tr>
<td>527.7</td>
<td>6/5</td>
</tr>
<tr>
<td>549.921</td>
<td>5/4</td>
</tr>
</tbody>
</table>

Note that this list is by no means exhaustive but rather reflects the sampling resolution, playback conditions, as well as my tuning experience at the time of the recording. The same experiment was then repeated with two samples of a cello tone (see Table 2), as well as a wide range of other timbres and instruments.
Similar empirical testings have been conducted by Marc Sabat with a variety of instruments, including contrabass, cello, viola, violin, and sampled organ reeds. He concludes that there are 213 tuneable intervals within the range of 1/1 – 8/1, many of which match with the two aforementioned lists.\(^5\)

A comparison of Sabat’s list with the ones provided above shows that, for the most part, the findings match, however, the list could be extended with various musical intervals labeled untuneable by Sabat. Despite the fact that, according to Sabat, the smallest tuneable interval is 8/7, several smaller intervals were found to be tuneable, albeit with greater difficulty. In the case of the sawtooth waves, below the threshold observed by Sabat, the intervals 16/15, 15/14, 13/12, 12/11, 11/10, 10/9, and 9/8 were found to be tuneable, in the case of the cello samples, 10/9 and 9/8 were found to be tuneable.

One possible explanation for this is the rich harmonic spectrum produced by a sawtooth wave, making the beating (and lack thereof) more apparent, thus suggesting the tuneability of a musical interval to be timbre-dependent. Moreover, the digitally synthesized sawtooth wave is perfectly stable, while acoustic instruments inherently fluctuate ever so slightly due to factors such as inharmonicity, nonlinearity in string tension, and the resonances of the body of the instrument. In addition, compared to acoustic instruments, digital control over pitch height allows for a higher incremental resolution, resulting in greater precision.

### Just Intonation – Rational Intonation – Perceptible Intonation

Although other kinds of intervals may be “approximated by a trained listener,”\(^5\) precisely tuneable intervals are always derived from a harmonic series, represented by frequency ratios comprising natural numbers. The difficulty with which those natural intervals can be tuned increases the higher up their spectral structure can be found within their respective harmonic series (making 3/2 easier to tune than 7/4 and 13/7 harder to tune than 8/7), echoing

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\(^5\) For Sabat’s complete list of tuneable intervals (contained within a 23-limit harmonic space), consult M. Sabat and R. Hayward, *Towards an expanded definition of consonance: Tuneable intervals on horn, tuba, and trombone*, pp. 6-10.

\(^5\) Sabat and Hayward, *Towards an expanded definition of consonance*, p. 4.
Schönberg’s assertion, that the lower a musical interval can be found within a harmonic series, the higher its comprehensibility as the ear is “less intimately acquainted” with higher partials.52

While the existence of the harmonic series in nature is well-documented, the subharmonic series is often considered a theoretical construct. However, subharmonic relationships can be observed in physical reality in various cases. For instance, certain instrumental playing techniques, such as overblowing in reed instruments, applying additional bow pressure in string instruments,53 and throat singing (for example, in the Tuval vocal tradition),54 can generate subharmonics. In addition, any system exhibiting nonlinear behavior, such as amplifiers, distortion pedals, compressors, and the human auditory system itself can, under certain conditions, produce subharmonics (as in the case of difference tones).

Based on my empirical observations, I have found that while the subharmonic series lacks the complete spectral fusion of its individual partials that is apparent in the harmonic series, the attribute of spectral fusion can still be observed up to the 6th subharmonic partial in most contexts.

For a long time, Western musical harmony has been described through the fractional representation of musical pitches, from Pythagoras (500 BC), who focused primarily on octaves, fourths, and fifths (an approach that carried over to the Middle Ages), to Gioseffo Zarlino who, in the renaissance era, introduced 5-limit major and minor scales by extending the Pythagorean (3-limit) approach with consonant thirds and sixths.55 56

Since only fairly recently – the 19th century, accompanied by the industrial revolution and the mass distribution of pianos – has this approach been dominated by and standardized to 12-tone equal temperament (12-TET), a system that divides the octave into twelve equal parts.57 However, since the mid-20th century, musical harmony based on whole number ratios has


53 For more in-depth information on playing subharmonics on a violin consult Mari Kimura’s webpage: http://www.marikimura.com/subharmonics.html [accessed April 2, 2023]


55 In just intonation, the concept of limit refers to the highest prime number used in the frequency ratios of the intervals of a tuning system. For example, a 5-limit tuning system only uses primes up to 5 (2, 3, and 5), while a 7-limit system uses primes up to 7 (2, 3, 5, and 7). A more comprehensive explanation of this concept can be found in The Just Intonation Primer by David B. Doty (p. 2).

56 Several Non-Western musical cultures have used whole number ratios to determine the tuning of musical intervals, such as a system of just intonation developed in the Zhou period (c. 1046-256 BCE) in Ancient China, as well as certain microtonal intervals in the Indian music tradition, also known as shruti.

enjoyed a resurgence, led by pioneers such as Harry Partch, James Tenney, La Monte Young among many others. While the conception of 12-TET is not rooted in any perceptual or physical reality but is rather borne out of a convenient standardization of musical pitches, allowing for flexible transposition between key signatures, some (but not all) just intonation practices do reflect and artistically acknowledge the acoustic and psychoacoustic properties discussed earlier, such as beatlessness, spectral fusion, periodicity, and strongly audible combination tones. Such an approach may be called perceptible intonation, offering an extension to what Catherine Lamb refers to as rational intonation. The American composer prefers the use of this term rather than just intonation, which historically has often been associated with 5-limit just intonation.

The distinction between perceptible intonation and rational intonation is proposed, as although all tuneable intervals can be expressed as ratios of integers, not all rational intervals are tuneable. For example, while the ratio 201:100 falls under the framework of rational intonation, its perceptual distinction from a nearby irrational interval is not immediately evident. It is critical to acknowledge, though, that while all intervals belonging to the framework of perceptible intonation can be expressed as ratios of integers, the description of musical harmony based on whole number ratios is merely a mathematical representation of the sound phenomenon. No matter how sophisticated any system may be, it cannot supersede the complexity of our perception.

Harmonic Framework: Overlapping partials of subharmonic-related harmonic series

The harmonic framework underlying the compositional method employed in XV XXVII III XXI IX: Variations is a network of closely related harmonic series whose fundamentals are derived from the subharmonic series (illustrated in Table 3). The presence of common partials among certain combinations of harmonic series creates the potential for shifting between these harmonic series, paralleling the concept of key changes in the context of Classical Western harmony. It is an extended just intonation system of varying complexity, borne out of the observation of certain auditory and acoustic phenomena, such as difference tones and (non)-beating, as well as the periodicity of composite sound waves.

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59 Interview from 1989 with La Monte Young about Just Intonation: http://www.dbdoty.com/Words/LMYInterview_01.html [Accessed April 9, 2023]
Table 3. Overlapping partials of subharmonic-related harmonic series.

The x-axis represents all odd-numbered integer submultiples of the fundamental (1/1), forming a subharmonic series (1/1, 1/3, 1/5, 1/7 … down to 1/27). The y-axis mirrors this behavior by constructing 27 harmonic series, defining each of the 27 subharmonics as a new subordinate fundamental. Any set of harmonic series can then be checked for common partials.

Such comparison of harmonic series is made easier by simplifying and octave-reducing the fractional representations of their partials. In the following example, the harmonic series with the fundamental of 1/1 is compared with the harmonic series with the subordinate fundamental of 1/3:

\[
\begin{align*}
1/1, 3/1, 5/1, 7/1, 9/1 & \rightarrow 1/1, 3/2, 5/4, 7/4, 9/8 \\
1/3, 3/3, 5/3, 7/3, 9/3 & \rightarrow 4/3, 1/1, 5/3, 7/6, 3/2
\end{align*}
\]

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62 Note that all ratios in Table 3 are in relation to 1/1.
This comparison shows that, when limited to their first five partials, there exist two common partials (1/1, 3/2) in the two harmonic series exemplified above, albeit their function will differ. While 1/1 is the 1<sup>st</sup> partial of 1/1, it is the 3<sup>rd</sup> partial of 1/3. Similarly, 3/2 is the 3<sup>rd</sup> partial of 1/1, but the 9<sup>th</sup> partial of 1/3. This method can be extended to all present subharmonic identities, allowing for relationships of varying complexity.

Among other compositional techniques, this gives way to the possibility of shifting between two subharmonic-related harmonic series, utilizing their common partials as connecting points. In the case of XXI VII III I, an audiovisual piece in collaboration with Derek Holzer on laser phase synthesis, the fundamental 1/1 was assigned to 440 Hz. Three other subordinate fundamentals, each containing its subset of unique harmonic partials, were chosen (1/3, 1/7, 1/21). Subsequently, their order was determined by calculating their respective closest relative, forming the *path of least resistance*. In alternative terms, the harmonic identity of 1/21 is closest to that of 1/7 while the harmonic identity of 1/3 is closest to that of 1/1, as they are the combinations that share the most common partials. An excerpt of the resulting sequence is illustrated below. Each fundamental is held for x amount of time, while the common partials overlap. It is important to note, that the octave in which each fundamental or partial is present is not fixed but depends on the timbre used (as will be discussed below).

![Diagram of harmonic series and fundamentals](image)

*Figure 6. Score excerpt of XXI VII III I*

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63 Video documentation of a performance of the piece in Falun, Dalarna in November 2022: [https://www.youtube.com/watch?v=TxTR7NiVA3k](https://www.youtube.com/watch?v=TxTR7NiVA3k) [Accessed April 12, 2023]
The primary timbres used as sonic material for *XXI VII III I* were sine waves and samples of several gongs and bells. While the sine waves were tuned to precision in the PureData environment,\(^{64}\) they interacted with the inharmonic spectra of the percussion instruments, resulting in rich interference patterns, which are reflected in both sound and visualization. As the piece progresses, the sine waves are processed using several analog distortion units, adding yet another layer of harmonics. Through this, the resulting difference tones – which at first are only present in the perception of the listener, in the form of otoacoustic emissions – are materialized in the physical space via intermodulation distortion (IMD).\(^{65}\)

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\(^{64}\) Pure Data (Pd) is a free and open-source visual programming language for creating computer music and multimedia works. For more information, visit [https://puredata.info/][Accessed April 1, 2023]

\(^{65}\) This collaboration is dealt with in more detail as part of the forthcoming paper *Laser Phase Synthesis [XXI VII III I]* by D. Holzer, L. Aron, accepted for publication at the New Interfaces for Musical Expression conference (NIME), in Mexico City, (2023).
DISCUSSION

I believe that compositional techniques that “play the ear” are effective catalysts for reaching states of mind that transcend the mundane. However, the use of compositional techniques that elicit auditory artifacts also raises ethical concerns, as one is quite literally taking control over another person’s body, considering the largely involuntary nature of these phenomena – “the ears don’t have eyelids.” But one could argue that this is the case in any presentation of sound, where there is a sort of unwritten contract of consent between audience and musician. There is, however, still a great responsibility on the side of the sound engineer to keep sound pressure levels within an appropriate range. An approach that is both considerate towards the audience’s health and mindful of the composer’s intentions is necessary. A disclaimer of expected sound pressure levels and an introduction or program note, including reassurance about the harmlessness of the to-be-presented sound can help building trust and creating an ideal setting.

Via the use of some just intonation techniques, certain perceptual features can be emphasized, although it is important to acknowledge that the psychoacoustic phenomena discussed in this thesis are not exclusive to just intonation. During a conversation that took place after an organ tuning session with Jan Börjeson, one student commented: ‘But there is so much sound in between!’ – referring to the complex and captivating beating patterns that were aimed to be eliminated in the pursuit of achieving perfect unison between the respective reed and flue pipes of the organ. In this way, the act of tuning is as much a perceptual practice as an aesthetic choice.

Similarly, it can be valuable to be aware of the existence of the path of least resistance in the harmonic framework provided earlier in the text, but it might not always be artistically desirable to follow it strictly, as a lot of the resulting harmonic movements are reminiscent of functional harmony in Western classical music. Nevertheless, the path of least resistance is a fascinating way to explain various intuitive musical choices already in place. In the case of XV XXVII III XXI IX: Variations, however, the algorithmic interventions were dealt with more freely, often choosing the 2nd or 3rd nearest subharmonic identity.

Ultimately, the main motivation behind my musical practice is to induce alternate listening modes, in which even subtle changes in the music take on a heightened perceptual significance. According to James Tenney, it is consequential that listening modes will change according to the structure of a given piece of music. He states that when the “perceptual scale of the music is reduced,” this, in turn, will “encourage the perception of smaller details.” By taking the reduction of sensory information to an extreme, more responsibility is put on the listener. By leaving space in the music, each individual listener is free to superimpose their own imaginative music, informed by their own experience and background, on top of what is


68 J. Tenney, Meta (+) Hodos, Inter-American Institute for Musical Research, Tulane University, 1964, p. 11.
audible. This is a realization that came forth from the post-concert feedback of several audience members, who mentioned hearing melodies within the sustained chordal structures central to my music – melodies not physically present, but imagined, as the listening mind is deprived of stimuli. Naturally, this affords a certain degree of attentiveness and openness that cannot be taken for granted – qualities that could be practiced in the Deep Listening meetups I host in Berlin and Stockholm since 2020, in which both musicians and non-musicians are welcome. In the spirit of Deep Listening pioneer Pauline Oliveros’ practice, there is a difference between the involuntary nature of hearing and the voluntary, selective nature of listening.\(^{69}\) In fact, in my own practice, I aspire to adopt an approach where the composer is primarily a listener – a notion that, on the surface, may seem self-evident, but as I hope this text has shown, presents itself as a more subversive act than it first appears.

BIBLIOGRAPHY


