BEATINGS: A WEB APPLICATION TO FOSTER THE RENAISSANCE OF THE ART OF MUSICAL TEMPERAMENTS

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ABSTRACT

In this article we present *beatings*, a web application for the exploration of tuning and temperaments which pays particular attention to auditory phenomena resulting from the interaction of the spectral components of a sound, and in particular to the pitch fusion and the amplitude modulations occurring between the spectral peaks a critical bandwidth apart. By providing a simple, yet effective, visualization of the temporal evolution of this auditory phenomena we aim to foster new research in the pursuit of perceptually grounded principles explaining Western tonal harmonic syntax, as well as provide a tool for musical practice and education, areas where the old art of musical tunings and temperaments, with the notable exception of early music studies, appears to have long been neglected in favour of the practical advantages of equal temperament.

1. INTRODUCTION

The history of tunings and temperaments in Western music is closely related to the evolution of compositional practice, from Pythagorean tuning and its perfect consonances of octaves, fifths and fourths to equal temperament and the spread of chromaticism. From its peak development phase in the common-practice period, tonal music has evolved in numerous ways to become a particularly successful syntax – one that still forms the basis for musical training in Western culture –, forming a plethora of tonal composition idioms such as today's pop and jazz music. Harmony is a primary, well-research element of tonal syntax, to which many theories have been devoted. These explain the principles regulating the tonal music syntax, by abstracting archetypical structures and rules from large corpora of Western tonal music [1, 1–6]. Each of these theories emphasizes different aspects that regulate harmony, including voice leading [2, 5], root progression [3, 4], and tonal tension [6] in an axiomatic and formalized manner.

More recently, psychoacoustic and cognitive studies have shown that the aesthetic origin of Western tonal harmony syntax appears to be consistent with perceptual auditory streaming principles [7–9]. Parncutt [7] presented a comprehensive theory of musical harmony explained by psychoacoustic and pitch-related elements of music perception. Huron [8] was particularly successful in outlining most axiomatic principles within Western tonal harmony theories from a perceptual viewpoint. These new findings not only prompt a new understanding of the auditory mechanisms regulating harmony, but can also promote new compositional strategies.

Motivated by the possibility to study auditory phenomena and draw a research agenda on topics across cognitive psychology and music theory, we present *beatings*, a web application for the real-time visualization of amplitude modulations and fusion created by the interaction of spectral peaks. These sensory phenomena are known to have an impact on the perception of consonance and dissonance [7, 10, 11] and, to the best of our knowledge, no other application allows the visual exploration of these phenomena in an explicit way.

Many potential applications exist for our work. First, it allows the performance of music using different tunings and temperaments readily from the browser, surpassing the need for an (historical) instrument which is able to cope with adjustable tuning. As an ear training tool, for the music student and/or professional tuner, *beatings* can offer a refined level of control over the several components tones of harmonic intervals. Furthermore, it offers a simple way to perform with different tuning systems, while analysing the interaction between spectral harmonic peaks in an accurate way. Finally, *beatings* constitutes a platform for future research in tuning, temperaments, and the acoustics of musical scales and harmony, in particular by unveiling physical correlates of sound. Untimely, by highlighting the direction of spectral peaks and interaction over time, we hope that *beatings* may shed some light on a limitation of Huron's [8] theory, which lacks an explanation for the sense of direction ("leading") that attends musical pitch successions in tonal Western music. As it stands, Huron's [8] perceptually-derived voice leading rules are equally effective in both directions, which clearly does not capture the essence of harmony writing in cases where contingent resolutions are required such as embellishments (e.g., suspensions, appoggiaturas) or the common voice leading of the third and seventh of dominant chords.

The remainder of this article is structured as follows. Section 2 reviews psychoacoustic phenomena of pure and complex tone interactions within one critical bandwidth as the basis of the mechanics and design principles of our web application, whose implementation we detail in Section 3. Section 4 presents an extensive plan for future work per application area, shedding some light on the possible uses of the application as well as phenomena and problems it might allow us to observe and equate in greater detail. Section 5 concludes the paper and summarizes our contribution.

2. CRITICAL BANDWIDTH: FROM FUSION TO BEATINGS TO ROUGHNESS TO SMOOTHNESS

The critical bandwidth is a term coined by Fletcher [12] to describe the frequency bands of the human 'auditory filters'. These bands regulate innate auditory phenomena, including the tone sensations evoked by the superposition of frequencies, relevant to our paper.

Considering two frequencies f_1 and f_2 in Hz, instantiated at the same frequency and gradually displaced by increasing f_2, we now describe two important physical correlates of sound that occur within a critical band: frequency discrimination and beatings.

First, a single tone or unison is perceived when the frequencies are identical up to the limit of frequency discrimination, when two tones start to be perceived. The human ear tends to fuse the two tones up to a difference of between a half- and whole-tone (for the pitch register of musical instruments) depending strongly on the critical band and the individual [13]. Stumpf [14] developed this phenomena by drawing a theory of tonal fusion which explains "the tendency for some concurrent sound combinations to cohere into a single sound image" [8]. In [15], Huron showed that in the polyphonic writing of J.S. Bach, intervals that promote tonal fusion are avoided in favour of discernible lines, or clear independence across voices.

Beatings are an auditory phenomena created by the phase interaction (i.e., reinforcement and cancellation) between tones within a critical band. Perceptually, it results in a variation of volume (i.e., amplitude modulation) whose rate, or frequency f_b in Hz, can be calculated as the difference between the two frequencies, such that:

$$f_b = |f_2 - f_1| \tag{1}$$

When f_b is approximately 10 Hz we perceive 'slow' beatings, whose modulation rate can be easily followed by the ear. Musically, this effect is referred to as tremolo [16]. When the beatings' frequency increases to around 20-30 Hz, the tremolo sensation ceases to be heard and, instead, 'fast' beatings create roughness – an unpleasant sensation perceived up to one critical bandwidth. Above this limit, the roughness sensation between two pure tones is replaced by a smoothness sensation. Figure 1 summarizes the different perceptual phenomena resulting from the interaction of two frequencies in terms of identifying the transitions between the auditory phenomena mentioned above. Although Figure 1 establishes exact frequencies as limits for several auditory phenomena, these are rather mean values extrapolated from listening experiments, which may vary between individuals.

Partials of complex tones are also known to produce a beating sensation when they are a critical bandwidth apart, thus following the same principles detailed for two frequencies. As a result, the timbre of complex tones can

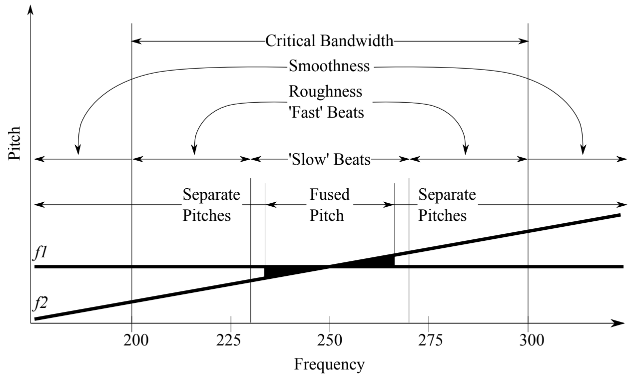

Figure 1. Pure tones interaction in terms of their perceptual fusion and beating qualities (adapted from [13]).

affect our experience of several perceptual phenomena dictated by the critical bands. Fast beats, also know as roughness, have been recognized to be one of the most relevant aspects of innate influences on the perception of (sensory) dissonance, and thus affect our subjective experience of musical and harmonic dissonance [11, 13, 17].

3. APPLICATION

beatings currently exists as a web application,[1] developed using p5.js [18], and is compatible with any desktop browser that supports the Web AUDIO API [19]. However, it is only fully functional in browsers that also support the Web MIDI API[2] [20]. In this section, we will detail its implementation and describe the most relevant user interface design decisions.

3.1 User Interface

The user interface of *beatings* (as seen in Figure 2) takes the form of circle divided in twelve parts that represent the division of the octave into notes, as established by the currently selected temperament. This representation was inspired by [11] and always includes the division of the octave in twelve equal parts (i.e., equal temperament) in a lighter tone for comparison. The detuning from equal temperament in cents is shown, also in a lighter tone, around the correspondent note name. Inside this main circle, a spiral represents approximately 8 octaves, with one turn per octave from A0 to C9, as inspired by the recent "The Snail" plug-in by IrcamLab [21].

To add a notes, the user can click on any note name to activate or deactivate it. To change the octave of an activated note, the user can click on one of the intersections between the note radius and the spiral and drag it up or down to change the octave. The lowest of the selected notes is represented by an arrow pointing to the centre of the circle and all of the currently selected notes are represented in a musical score visualization on the bottom left corner of the interface.[3] The number of harmonic partials shown for

[1] available at http://ruipenha.pt/beatings/.

[2] At the time of writing, only Chrome and Opera have Web MIDI support.

[3] All note representations can toggle between the use of sharps or flats by pressing the **f** key.

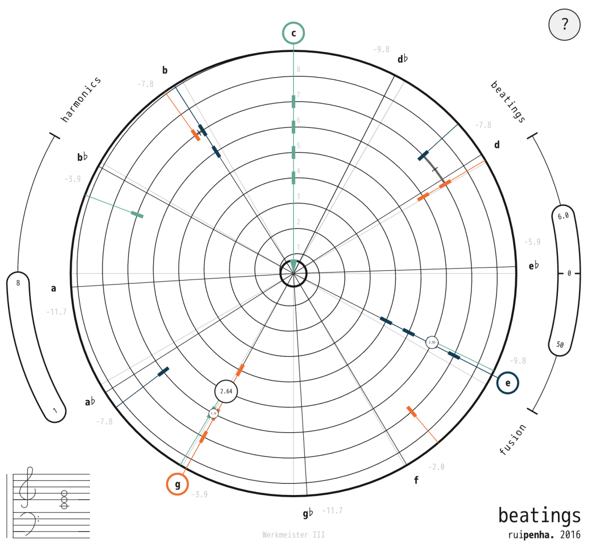

Figure 2. The graphical user interface of *beatings* showing a C major chord in the Werkmeister III temperament.

each selected note can be set using the interface element to the left of the main circle. To change the tuning of the last selected note, the user can use the **up** and **down** keyboard arrow keys to change it one cent[4] (or 0.1 cents, by holding **shift**) up or down, respectively.

By pressing and holding the **spacebar**, the user can listen to the currently selected notes. Each harmonic partial n shown is synthesized by a sinusoid of amplitude a

$$a = \frac{1}{n} \tag{2}$$

thus approximating a sawtooth wave.

Slow beatings are visualized by a circle that is centred at the middle frequency between the interfering partials. This circle expands and contracts at the frequency of the slow beating, also shown inside the circle, with its maximum and minimum amplitudes being proportional to the maximum and minimum amplitudes of the slow beating. This visualization aims to stimulate the auditory perception of the slow beating via multimodal perception. The criteria for this visualization can be set by adjusting the maximum frequency of the slow beatings shown by using the interface element at the top right of the main circle.

The fusion of partials is visualized by a grey arch that connects the interfering partials, with the middle frequency between those represented by a small slash. The criteria for this visualization can be set by adjusting the maximum interval in cents, using the interface element to the bottom right of the main circle. It is important to note that the criteria for both partial interference visualizations are set by the user and thus do not precisely represent the psychoacoustic limits as established by the relevant literature, even if these limits were taken into account when defining the respective range of the interface elements.

[4] I.e., one cent of a semitone, corresponding to an equal division of the octave in 1200 cents.

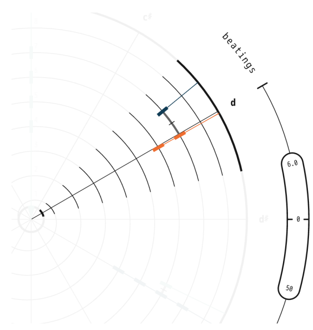

Figure 3. Detail of the graphical user interface of *beatings*, showing the isolation mode.

key	tuning / temperament
0	Equal Temperament
1	Pythagorean
2	Pietro Aaron (meantone)
3	Werkmeister III
4	Thomas Young
5	Just Intonation 1
6	Just Intonation 2
7	Just Intonation 3

Table 1. Default tunings and temperaments included in *beatings*.

To facilitate the auditory perception of these partial interferences, the user can press the key **i** to enter the isolation mode. This mode enables the isolation, by moving the mouse around the circle, of a particular part of the main circle for sound synthesis (as shown in Figure 3).

Some historical tunings and temperaments have been included in *beatings* and are accessible via the number keys, as seen in Table 1. While the selection of these tunings and temperaments is not exhaustive, it takes into account the history of European musical temperaments [11,22–24] and presents the main representative of pre-renaissance tunings (Pythagorean), one representative of renaissance meantone tunings (Pietro Aaron), one representative of baroque tunings (Werkmeister III), one representative of classical tunings (Thomas Young) and the ubiquitous equal temperament and just intonation. Just intonation is represented in three versions, all referring to C, in which the notes corresponding to D, F sharp / G flat and A sharp / B flat are tuned to, respectively: 1) minor tone, augmented fourth and harmonic minor seventh; 2) major tone, diminished fifth and grave minor seventh; 3) major tone, diminished fifth and minor seventh.

Finally, it is possible to export the current visualization as a PDF, by pressing the **s** key. As it is impracticable to convey the slow beatings in the PDF file using the same strategy as in the web application, these are represented by indexes inside the main circle (as seen in Figure 5). These indexes refer to the detailed descriptions that appear in a table to the right of the main circle, sorted in descending order from the maximum amplitude.

3.2 Web MIDI API

It was decided early on to use the Web MIDI API [20] in *beatings*, even if this standard is still in its early stages of deployment and, at the time of this writing, available only on a limited number of web browsers. This API provides easy access to the MIDI interfaces connected to the machine running the browser, allowing the use of MIDI controllers as an additional note input strategy. This permits the real-time playing of music in different temperaments or the rendering of MIDI files, using an inter-application MIDI router, such as the IAC Bus (on Mac OS X).

4. PROPOSED RESEARCH DIRECTIONS

4.1 Application improvements

We intend to continue the development of *beatings* by adding additional features to improve its merits as both a musical instrument and a research tool. The application currently lacks a way to save and retrieve temperaments and, consequently, a convenient way to share the users' proposals. Also currently missing is an easy way to embed playable custom temperaments or interval examples in web pages, which could be used to facilitate the dissemination of examples. A built-in MIDI player could facilitate the experience of the effect of different temperaments in different musical pieces. Finally, providing additional controls over the synthesis parameters (such as the global envelope or the amplitude and tuning of individual partials) would enhance not only the usefulness of *beatings* as a musical instrument, but also its ability to provide a more meaningful experience of the relation between timbre, tuning and the perception of consonance and dissonance [11].

4.2 Research in voice leading

As previously mentioned, our main motivation for the development of *beatings* was to enable further research in voice leading within tonal harmony, something we intend to pursue in the near future. The relationship between the history of tunings and temperaments and the evolution of harmony in Western musical culture is to be expected and has some striking coincidences, such as the apparent contiguity between the arising of meantone temperaments, that began altering the perfect fifths of Pythagorean tuning to favour consonance in thirds, and the transition of the fourth from the status of a perfect interval to the status of a dissonance, to be resolved downwards towards a third. If we observe a fourth between, e.g., C4-F4 in *beatings* using Pythagorean tuning (Figure 4) and using Pietro Aaron's meantone (Figure 5), we can easily see (and hear) that the stable fourth of the former is, in the latter, rendered unstable by the prominent slow beating of approximately 3.24 Hz between the fourth partial of C4 and the third partial of F4. The shortest path to resolve this instability is to descend the F4 to E4, that in Pietro Aaron's meantone temperament corresponds to the just intonation of the major third of C4 and is thus particularly consonant. Can we find more examples such as this one? Can the interrelation of slow beatings, fusion and the sensation of musical scale help to create the urge to lead specific voices up or down to solve particular dissonances?

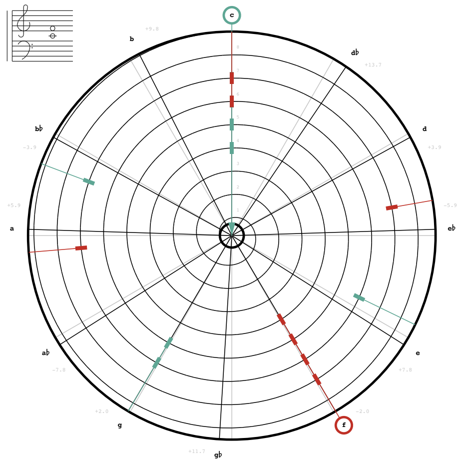

Figure 4. C4-F4 interval (perfect fourth) in Pythagorean tuning, shown with 8 harmonic partials for each note.

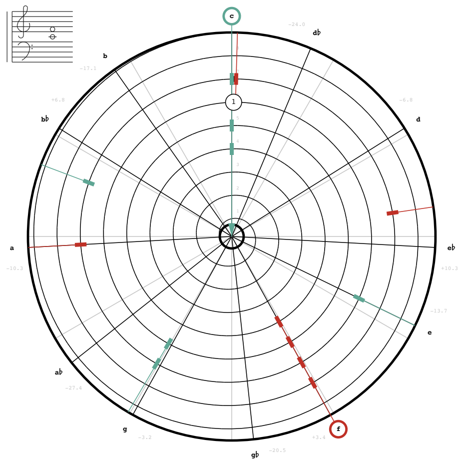

Figure 5. C4-F4 interval (perfect fourth) in Pietro Aaron's meantone temperament, shown with 8 harmonic partials for each note. The slow beating with label (1) has a frequency of approximately 3.24 Hz.

4.3 Beyond the Twelve-Tone Division of the Octave

An obvious limitation of *beatings* is the exclusive reliance on the twelve-tone division of the octave. This decision is related not only to the prevalence of this division in Western musical culture, but also because of the reliance on the MIDI protocol and the ubiquity of the keyboard as a MIDI interface. We would like, however, to include the capability of exploring tunings and temperaments with different divisions of the octave, acknowledging the contribution of other musical cultures to the art of tuning and temperament, as well as the inspiring work of Western composers such as Harry Partch.

5. SUMMARY

In this paper we have presented *beatings* and some of our motivations for its development. We believe that this application provides a novel and compelling way of exploring tunings and temperaments. The straightforward availability via web browser, along with the real-time synthesis and MIDI control capabilities, might help contemporary musicians to get acquainted with the effect of different tunings and temperaments, adjust them and choose before actually retuning an acoustic instrument (e.g., a harpsichord) or before searching for the same temperament in non-fixed tuning instruments (e.g., voice or bowed string instruments). In acoustics and psychoacoustics classes, the multimodal experience of slow beatings and the possibility to easily isolate fusion phenomena might prove helpful for students to explore and better understand the acoustical properties of harmony within different musical tunings and temperaments. Finally, we hope to contribute to the renewal of the interest in tunings and temperaments and, in particular, to the research of their impact on harmony and voice leading.

Acknowledgments

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