INTERACTIVE MUSICAL PERIODIC TABLE: SONIFICATION OF VISIBLE ELEMENT EMISSION SPECTRA

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ABSTRACT

Is the periodic table a musical instrument? While this may seem like an absurd question, the process of data sonification can be used to convert the visible spectra of chemical elements into sounds. Each element releases distinct wavelengths of light depending on its electron energy levels—a sort of “chemical footprint” unique to every element. These frequencies of light, which we perceive as different colors, can be represented as frequencies in the audio domain, allowing us to “hear” each distinct color as a sine wave with a unique frequency. This research project involved the construction of an interactive musical periodic table, combining visual representations with sonifications of elemental spectra from high-resolution spectral datasets. Implemented in Max/MSP and Jitter, the program provides audiovisual displays of each element from its rich spectral data. The user can listen to all spectral lines of an element simultaneously (chord mode), or individual lines in succession (melody mode). Future work will involve implementation of this tool in K-12 classrooms to evaluate its efficacy as an interdisciplinary teaching tool bridging STEM and the Arts.

1. INTRODUCTION

The field of chemical spectroscopy concerns the study of atoms and molecules using electromagnetic radiation. Connections between chemical spectra and acoustic spectra have been made by Delatour, who proposed methods for the auditory representation of molecular vibrational spectra [1]. Sonifications of molecular vibrational spectra have been employed by chemical education researchers to develop tools for auditory analysis of chemical spectra for blind and visually impaired students [2]. Nuclear Magentic Resonance (NMR) Spectroscopy is another technique that has enjoyed a productive relationship with music and sound; NMR sonifications have been applied to chemical education [3] and auditory analysis of spectra [4]. NMR and other spectral data has also provided inspiration and musical material for composers [5], including in prior work by the author in "The Sound of Molecules" [6], where sonifications of NMR spectral data are accompanied with narration to create a "sonic tour of the molecular world.

The analytical techniques discussed above use regions of the electromagnetic spectrum that are not visible to humans (infrared and radio-frequency radiation for molecular vibrations and NMR, respectively). However, atoms and molecules can also absorb and emit visible light. When stimulated by a large amount of energy, atoms produce visible emission spectra–vibrant collections of colors resulting from electrons within atoms changing energy levels [7]. Sonifications of these spectra can be accompanied by the corresponding visual spectra as a tool for audiovisual composition. This is demonstrated in the author’s composition "Chromatic Chemistry," in which the spectrum of helium is sonified and used to create an audiovisual "Helium Dance Party" [8]. These multimodal representations could also potentially be used for spectral data analysis and/or chemical education.

The Interactive Musical Periodic Table presented here is a natural extension of the author’s prior work creating live music/science shows based on chemical sonifications like "The Sound of Molecules" [9]. The goal of this project was to design a prototype of an interface that both the author and others could use to listen to sonifications of the visible spectra for all the elements in the periodic table.

2. METHODS

2.1 Mapping light to sound

Analogies between light and sound extend so far into scientific history that Newton’s assignment of the seven discrete colors (red, orange, yellow, green, blue, indigo, and violet) to the continuous light spectrum was done so that the number of colors would match the number of tones in the Western 7-note diatonic scale [10]. Newton’s color circle published in his *Opticks* [11] associates the colors with the notes of a D dorian scale, beginning with D (red) and ascending to C (violet) as shown in Figure 1.

Remarkably, even though Newton did not measure the wavelengths of the different colors of visible light (these were not determined empirically until 1802 by Young [12]), the relationships Newton devised are remarkably close to reality; the ratios of wavelengths (and thereby frequencies) of different colors of light and the ratios of the corresponding musical notes to which Newton associated them are more or less correct. This is because the visible spectrum spans very nearly one "octave" of light; the highest frequency light (violet) has roughly double the frequency of the lowest-frequency light (red). Thus, associating the visible spectrum of light with an ascending scale

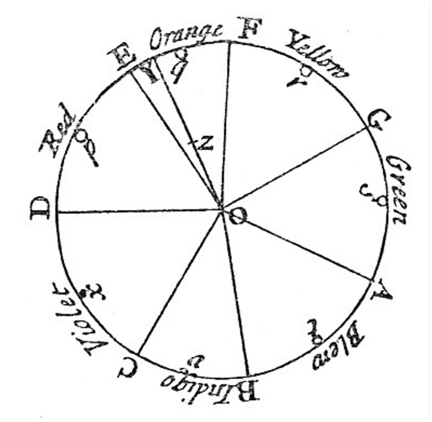


Figure 1. Figure from Newton's *Opticks* illustrating his association of notes of the D dorian scale with the colors of visible light.

from red to violet is a very close approximation of what colors would sound like if we could listen to electromagnetic radiation.

Of course, even if we pretend that we can "hear" the electromagnetic waves that constitute light, the frequencies of visible light waves range from 380-750 THz, which is on the order of 10^{11} to 10^{13} times larger than the frequencies humans can hear. Multiplying the frequencies of light by a scaling factor in the range of 10^{-11} to 10^{-13} places them comfortably into the human hearing range of 20-20,000 Hz. Scaling the frequencies of visible light like this is equivalent to conceptualizing of them as a musical scale and transposing it into an octave that humans can hear.

As the human hearing range spans 9-10 octaves, this gives us a choice of which octave of sound we choose to place visible light (and therefore, the visible spectra of the elements). Different factors may lead a scientist or composer to choose a certain octave in which to place visible light; for this work, a combination of practical and aesthetic decisions guided the selection of the range of 380-750 Hz (obtained by multiplying the light frequencies by the scaling factor of 10^{-12}) as the default setting for sonification of elemental spectra. This frequency range (roughly corresponding to the middle of the piano, approx. F#4 to F#5), sits within the range of 250-4000 Hz, where the human ear has the greatest frequency discrimination (the average normal hearing adult can discriminate frequency differences of 0.2-0.3%) [13]. This practical consideration is important as two goals of these sonifications are for users to be able to (1) discern differences in elemental spectra purely by listening and (2) associate differences in sound with visual differences in the spectra. This range of 250-4000 Hz still contains several octaves, so an aesthetic decision guided further selection. Namely, at the lower end of this range, the spectra are more pleasant to listen to. When placed in a higher part of this range, such as the octave of 2,000-4,000 Hz, the spectra with hundreds or thousands of distinct lines can result in beating patterns that are more grating and unpleasant than they are in the lower range of 380-750 Hz. Thus, placing the spectra in this range represents the best aesthetic decision from the perspective of the author. That said, there is a slider in the GUI for the musical periodic table that allows users to change the scaling factor, thus changing the octave that the sound is in. In future work, evaluating users' assessment of (1) the pleasantness and (2) ease of audible discrimination between different elemental spectra would allow for a more empirically-based determination of a default octave for the spectra.

The decision to map the frequencies of light via a direct, linear scaling process should also be noted. This particular method considers the collection of light frequencies as a musical scale, and the scaling operation as equivalent to transposing that scale. This direct transposition process retains all of the musical intervals exactly, whereas other mappings would distort these musical relationships. Notwithstanding, alternate mapping protocols could lead to other interesting musical structures and potentially have value as an auditory data representation, and these considerations are discussed in section 4.

2.2 Sonification of Element Spectra

Each element possesses a unique atomic emission spectrum, a series of lines with discrete frequencies of light (i.e. colors) that result from electrons changing energy levels within atoms. A selection of emission spectra is included in Figure 2.

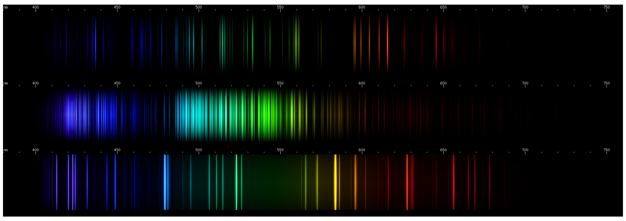


Figure 2. Examples of three element spectra. From top to bottom: oxygen (O), iron (Fe), and gold (Au).

These spectra are useful for identifying elements in chemistry and other fields, for example identifying trace heavy metals in water or discerning compositions of stars. Spectral data was obtained from an online database [14] of high-resolution emission spectra (compiled from datasets from MIT Wavelength Tables [15] and the NIST Atomic Spectrum Database [16]), in the visible range of 380-760 nm. These data were collected into TSV files, which are read in the Max/MSP patch. For each spectral line, a unique sinusoid is generated with the frequency corresponding to the frequency of the light, and the amplitude corresponding to the line's intensity. The amplitude values are normalized so that the sine wave resulting from the most intense line for each element has an amplitude of 1. As these spectra are amplitude spectra and contain no phase information, the initial phases of all sinusoids are set to 0. The sonification of helium's emission spectrum via this process is shown in musical staff notation in Figure 3.

As these spectra yield rich microtonal collections, they cannot be notated in a 12TET notation system. Cent de-

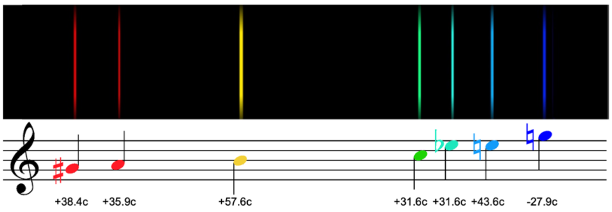


Figure 3. Sonification of helium's visible emission spectrum by scaling the frequencies of light down by 10^{-12} to produce a unique musical pitch for each color. Cent deviations are included below the notated pitch to show the actual frequencies of helium's sonification (where 100 cents = 1 semitone).

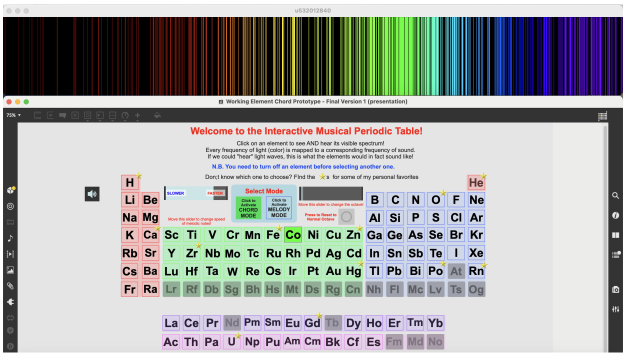
viations are included below the notes to indicate the actual frequency. The Max object ioscbank∼ is used to efficiently generate the large numbers of sine waves (which can be up to 2000 for some elements) from an array of amplitudes and frequencies. This object also enables smooth interpolation between changing frequency inputs, which allows the user to smoothly transpose the entire spectrum to a different range as discussed in section 3.

2.3 Visual Display

The visual display is generated using Jitter, with the brightness and width of each line scaled proportionally to its intensity. It is impossible to accurately represent every single spectral color with the RGB color space used in computer visuals, so an approximation method [17] was used to convert wavelengths of light into RGB values.

3. INTERACTION DESIGN

In the main window of the Max patch in presentation mode, shown in Figure 4, users can click on an element to see its spectrum and hear a sonification of it.



Welcome to the Interactive Musical Periodic Table!

Click on an element to see AND hear its visible spectrum!
Every frequency of light (color) is mapped to a corresponding frequency of sound.
If we could "hear" light waves, this is what the elements would in fact sound like!

N.B. You need to turn off an element before selecting another one.

Don;t know which one to choose? FInd the ★s for some of my personal favorites

Figure 4. GUI for the Interactive Musical Periodic Table, designed in Max/MSP and Jitter.

The spectrum is displayed in a separate jit.world window, which can be displayed on the same screen, but ideally on a separate monitor or with a projector in a dark room for best effect. A user can select "CHORD MODE" to see and hear all spectral lines at once, or "MELODY MODE" to iterate through the lines one-by-one (with a short sinusoidal pulse synchronized to the appearance of each line) from violet to red (high frequency to low frequency). Within "CHORD MODE" one can also scale the octave of sound that the visible light is scaled to, and press a button to return to the default range of 380—750 Hz. Finally, within "MELODY MODE," the user can also alter the speed of playback of the lines.

The labels for the elements in the GUI are colored according to their block in the periodic table. Certain elements are greyed-out as these elements are too radioactive to measure their spectra, hence no spectral data is available and no are not sonified.

One aspect of the user design that has proved problematic is that users are required to turn off their current element selection before selecting another one. the next user need to be explicitly told this and often forget. The table only displays the visuals and audio for the last selected element, so this does not create an issue with the sound or visuals. However, this results in a number of elements remaining selected, requiring the next user to first de-select an element they would like to hear and then re-select it. Future implementations will address this issue.

4. RESULTS AND DISCUSSION

The sonifications obtained from the interactive musical periodic table vary from simple sonorities resembling tonal structures to complex noises. Simpler elements like hydrogen and helium contain only a few lines, and thus yield relatively simple combinations of tones. These simple elements can even create recognizable chords. Hydrogen has four spectral lines that form a sonority resembling a second-inversion minor chord with an added second scale degree, while helium sounds like a diatonic cluster. Users are often surprised by how closely some of the elements resemble tonal sonorities-especially that hydrogen sounds like such a simple, recognizable chord. It should be emphasized that these resemblances to tonal structures are not the result of any tempering or quantization to a chromatic or diatonic scale. Rather, hydrogen forms a microtonal pitch collection that happens to be very close to a minor chord with an added second scale degree.

While some elements–especially those towards the beginning of the periodic table with only a few electrons and therefore few spectral lines–sound like simple, tonal chords, most elements have hundreds or thousands of lines and yield much more complex, noisy clusters. Because of this, many elements become difficult to distinguish from other elements. For example, oxygen and iron sound relatively similar despite the fact that iron has approximately ten times as many spectral lines as oxygen does. This makes sense as an incredible wealth of information is being compressed into a single octave of sound. Even so, differences in elements become apparent with continued and attentive listening, just as one can learn to differentiate between different colors of noise. Additionally, the compact clusters of sine waves result in different beating patterns for the different elements, which can aid in differentiating the sounds (provided that one is able to listen for more than a few seconds).

In the author's experience, it is sometimes easier to distinguish between elements by listening to the spectral sonifications rather than looking at their visual spectra, which are also quite complex and difficult to distinguish without study. Of course, this represents a sample size of one, and the author's musical background presents a bias. Nevertheless, this suggests that this sonification method may be used to develop alternative tools for the interpretation of spectroscopy data, possibly for blind or visually impaired students or even as a supplementary tool to complement visual analysis. However, the present difficulty of distinguishing the spectra from sound suggests that a different mapping process from light frequencies to sound may be more effective in this regard–for example, one that makes use of the full extent of the human hearing range.

Visible emission spectra encode chemical properties of the elements, and there are some cases where these properties can be heard in the sonifications. For example, elements 22-30 comprise the first row of the transition metals, and include commonly known and very useful metals like iron, copper, nickel, titanium, cobalt, and zinc. All of the elements in this row, with the exception of zinc, produce dense visual spectra and correspondingly complex, noisy sonifications. However, zinc's comparatively sparse spectrum produces a simple, resonant chord reminiscent of a choir of angels singing with a delicate vibrato. Zinc's relatively simple spectrum–which can be clearly seen and also heard–is a result of its comparatively simple electron structure as compared to its other transition metal neighbors. This is just one example; further exploration of chemical properties and their relation to the sounds produced from these sonifications could provide a valuable tool for "hearing" trends in chemical properties in the periodic table. This could be useful in chemical education at the high school and collegiate level, as understanding chemical trends in the periodic table is an important but challenging part of the chemistry curriculum.

Compositionally, these sonifications provide an incredible repository of microtonal pitch collections that can be used to construct chords and melodies. This is demonstrated clearly in the author's "Helium Dance Party," where helium and other elements are used to make fun, groovy melodies. Additionally, the light-to-sound mapping can be applied outside of chemistry entirely, purely to develop colorful and eye-catching audiovisual representations of music. As the mapping of light to sound described in 2.1 associates one octave of sound with the full visible spectrum, octave equivalence can be applied such that each pitch class in a piece of music (with infinite microtonal resolution) can be represented as a single line with a unique color. One application of this is to develop synchronized light displays accompanying music for a "false synaeshtesia" experience. Such a program has been developed by the author, where users can upload a MIDI file and render a synchronized light show based on it [18].

5. CONCLUSIONS AND FUTURE DIRECTIONS

A basic prototype for sonifying the visible emission spectra of the elements was developed, and a GUI allows users to hear and see the spectra for each element. Continued refinement of the program and presentation of the tool to schools, along with surveys and assessments to gauge students' learning and interaction with the software, is in progress.

This work could potentially find application in areas spanning education, research, science communication, and composition. This work also has potential utility for spectroscopic data analysis. Sonification of spectral data is especially promising due to the fact that our ears essentially have a built-in Fourier transform; the basilar membrane in our ears deconstructs audio signals into their component sine waves. In contrast, our eyes do not possess this unique ability of spectral decomposition—that is why it is impossible for our eyes to separate out the red and yellow components from an orange paint, and why computer RGB displays can fool our eyes into thinking we see every color. We need prisms and/or computers to see the spectral components of light mixtures, but our ears pick out these spectral components automatically.

In this avenue, future work will involve experiments with focus groups to evaluate the ability of people (from musical and non-musical backgrounds) to distinguish between spectra visually and/or aurally to determine if sonification of visible element emission spectra is as effective as visualization of the spectra.

6. VIDEO EXAMPLE

A short video demonstrating the interactive musical periodic table in action, with examples of the element sonifications, can be found at the following link: `https://drive.google.com/file/d/1Vip9FK3LUlwAOh74fPBf_WBMF14fMBTZ/view?usp=sharing`

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