Music and Audio Programming: Assignment 3 Report
Sonification of Air Pollution Data

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1 Overview of the task

This assignment comprises sonification of air pollution data, using Bela, from two distinct periods: one week of April 2019 and one week of April 2020. Specifically, it tackles data concerning Mile End Road, London. To this extent data values are used to control a spectral delay procedure, changing the parameters of a series of bandpass filters and delay lines. By allowing a listener to actively switch between both sonifications, differences in pollution values from the two periods become aurally perceivable. A video demonstrating the outcome of the project is available at: `https://www.youtube.com/watch?v=uO5if7Xgi9M&feature=youtu.be`.

2 Background

2.1 Sonification

Historically, there are many examples that show that sound was the first choice for human beings for the representation and communication of information. As stated by Worrall, 'the idea that sound can convey information predates the modern era, and certainly the computational present' (Worrall 2018).

The emergence of the research field of sonification is marked by the occurrence of the first conference of the International Community for Auditory Display (ICAD) in 1992, held in Santa Fe, USA and founded by Gregory Kramer (Kramer et al. 1999). Since its beginnings, sonification has seen a rise in popularity (Supper 2012), linked to an increase in the availability of *big data* and the consequent notion that humans expect additional ways to enhance the comprehension of their surroundings (Scaletti and Craig 1991).

The most popular definition of sonification can be posed as '*the use of non-speech audio to convey information*' (Kramer et al. 1999). According to (Hermann, Hunt, and Neuhoff 2011), different types of sonification techniques can be classified as:

- **Audification -** data is mapped to sound pressure levels, thus becoming an audio waveform (Dombois and Eckel 2011);

- **Parameter-mapping sonification** - each data point is mapped to parameters of a sound event, being considered the most common technique of sonification (Grond and Berger 2011);
- **Auditory icons** - understood as aural metaphors in which the sound that is heard is a representation of an event, thus informing the listener of its occurrence, assuming prior knowledge about the link between sound and event (Brazil and Fernström 2011);
- **Model-based sonification** - use of an acoustic model that generates an output when excited, comprising a set of instructions towards interaction (Hermann 2011).

Furthermore, Barrass defines musification as a sonification technique that uses scales, chords, key and tempo changes (Barrass 2012), however it can be argued that this definition doesn't account for all compositional practices (e.g. musique concrète). In her doctoral dissertation, *Data Sonification in Creative Practice*, Bonet follows an approach on sonification from a more artistic perspective, extending the notion of musification as a sonification that is subject to musical constraints (Bonet 2019). Within this scope, a few possible interpretations can be considered: one that comprises a purely functional sonification that is bound to musical principles, other that is solely focused on artistic purposes, and something that is an approach in-between. Bonet supports her argument with Varèse's definition of music as 'organized sound' (Risset 2004), thus implying that a '*musification is an organised sonification*'.

3 Air Pollution Data

According to the World Health Organization[1], Nitrogen dioxide, NO_2, is the main source of nitrate aerosols, which form an important fraction of PM2.5 and, in the presence of ultraviolet light, of ozone. The major sources of emissions of NO_2 are combustion processes (heating, power generation, and engines in vehicles and ships).

For this assignment, data[2] concerning NO_2 values from a measuring site located on Mile End Road, London, was used. Specifically, it is comprised of hourly mean values from a week in 2019 (18^{th} to 25^{th} of April) and a matching week in 2020 (16^{th} to 23^{rd} of April). Data was downloaded into *.csv* files and was not subjected to any processing. An illustration of the data from both periods can be seen in Figure 1 and Figure 2. A raw comparison of the ranges of values in both graphs points towards a reduction of nitrogen dioxide emissions in the week of 2020.

[1] Retrieved from: `https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health`.

[2] Downloaded from: `https://www.londonair.org.uk`, a project by King's College London.

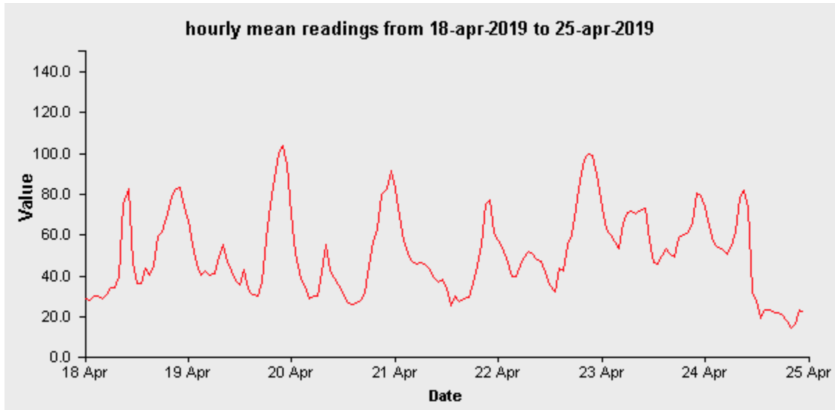

Fig. 1: Hourly mean nitrogen dioxide levels, in $\mu g/m^3$, at Mile End Road, London, from a week of April, 2019.

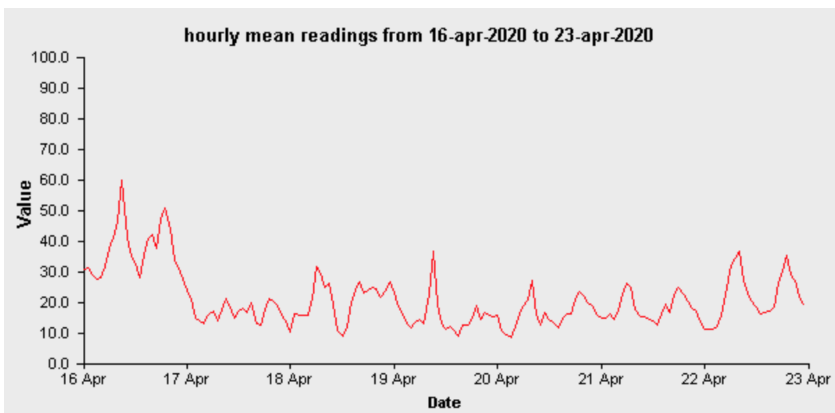

Fig. 2: Hourly mean nitrogen dioxide levels, in $\mu g/m^3$, at Mile End Road, London, from a week of April, 2020.

Recent reports point towards a positive impact in air pollution levels due to the lockdown policies related with COVID-19[3]. Thus, one of the motivations for this assignment was to inspect if information about such impacts could be conveyed by leveraging the audio modality. However, it is important to notice that causal relations between lockdown and air pollution quality are not possible to assess within the scope of this assignment, as it represents solely an auditory

[3] Retrieved from:`https://www.eea.europa.eu/themes/air/air-quality-and-covid19`.

depiction of data, which values, differences and variations might have occurred due other external factors.

4 Sonic Aesthetics

Aesthetically, this work explores the usage of *musical borrowing* in the sonification process, defined as 'deliberate evocation within a composition of a different musical work' (Bicknell 2001), where a piece of music (or a snippet of it) is used as source material to drive a new compositional process. As stated by Bonet for her piece *Wasgiischwashäsch*, it is important to note that this practice doesn't constitute plagiarism because it leverages audience's *musical literacy* and knoweledge about the originality of the piece (Bonet 2019).

For this project, a rendition of the piece 'Air on a G String', a Wilhelmj's arrangement of a Bach composition (2nd movemente of the Orchestral Suite No. 3 in D major, BWV 1068) was *musically borrowed*[4] for the process of sonification.

5 Implementation

Regarding implementation, first steps consist of using *SampleLoader.h* to load the audio file into a buffer. With *CSVReader.h*, air pollution data is stored into arrays. The sonification process is done by controlling parameters of a spectral delay effect, rendering this work as a parameter mapping sonification as described in Section 2.1. To this extend 10 bandpass filters were used, the output of each one stored into 10 delay buffer lines. Concerning the filters, its coefficients are calculated in *filterCoefs.h*. The spectral delay procedure is performed inside *render()*.

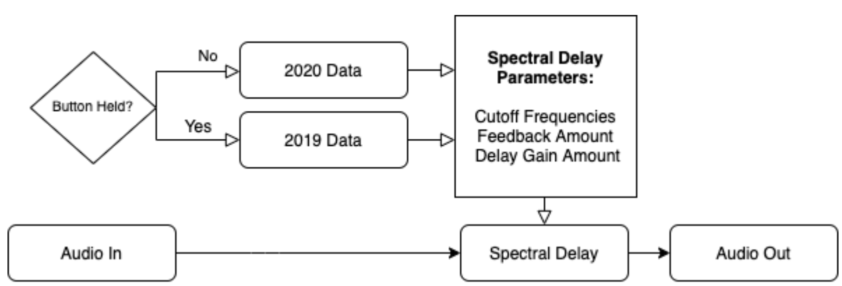

Fig. 3: Flow diagram of the sonification process.

A flow diagram of the steps in *render()* is depicted in Figure 3. Holding a button down switches from data of 2020 to data of 2019, subsequently altering spectral delay parameters such as cutoff frequencies of every filter, feedback and

[4] Downloaded from: `http://www.orangefreesounds.com/air-on-a-g-sring/`.

gain amount of every delay line. The output of every filter-delay line is summed and output.

5.1 Reading Data

In this step a procedure to read and retrieve data from *.csv* files was implemented in *CSVReader.h*. It comprises two major functions: *getSizeCSV*, which given a file returns the number of data points (or rows) on that file, and *getDataCSV*, that returns and array with data values from a column of the specified file. In order to dynamically allocate memory for the arrays, class template *std::vector* was used. After having both datasets stored in arrays, in *setup()* we calculate maximum and minimum values of both datasets, and store a global maximum and minimum in *gMaxGlobal* and *gMinGlobal* respectively. Finally, given the number of samples from the audio file, we calculate *gSamplesPerDataPoint*, the number of samples between every data point from both datasets (this step assumes that both datasets have an equal number of values). This is later used to calculate increments between every data point, aiming for a 'smooth' change of parameters.

5.2 Spectral Delay

As an audio effect, spectral delay can be implemented in a couple of ways. One consists of performing an FFT over the signal, and delay every frequency bin by a different amount, finally applying an IFFT to return to time domain. On the other hand, this effect can also be achieved with a series of bandpass filters, with a different delay on each filter output. This was the approach followed in this project, as depicted in Figure 4.

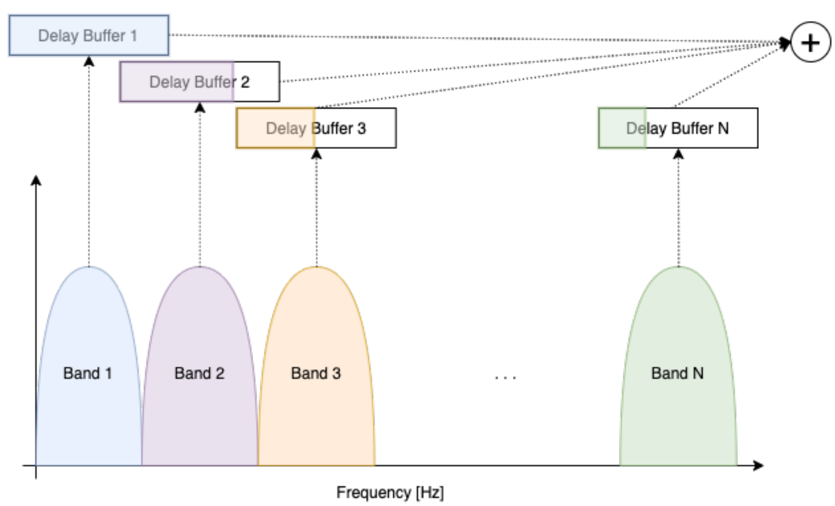

Fig. 4: Conceptual depiction of the implemented spectral delay process.

Bandapass Filter

In this step we implemented a 2nd-order bandpass filter, maintaining the filter's cutoff frequency (f_0) and qualilty factor (Q) user-adjustable. The transfer equation ($H(s)$) for a 2nd-order lowpass filter is given by:

$$H(s) = \frac{Y(s)}{X(s)} = \frac{(\frac{w_0}{Q})s}{s^2 + (\frac{w_0}{Q})s + w_0^2} \tag{1}$$

Here, s represents the complex frequency, and the highest order of s in the denominator determines the filter's order (Zumbahlen 2008). Furthermore, $w_0 = 2\pi f_0$ is the angular frequency of the filter cutoff, and Q is responsible for the resonating quality of the filter. Using the Bilinear transformation we arrive at:

$$H(z) = \frac{Y(z)}{X(z)} = \frac{(\frac{w_0}{Q})(\frac{2}{T}\frac{(1-z^{-1})}{(1+z^{-1})})}{(\frac{2}{T}\frac{(1-z^{-1})}{(1+z^{-1})})^2 + (\frac{w_0}{Q})(\frac{2}{T}\frac{(1-z^{-1})}{(1+z^{-1})}) + w_0^2} \tag{2}$$

Furthermore, to arrive at a 2nd-order IIR filter form, we first multiply both numerator and denominator of equation (2) by $QT^2(1 + z^{-1})^2$:

$$\frac{Y(z)}{X(z)} = \frac{(2w_0T(1 - z^{-1})(1 + z^{-1})}{4Q(1 - z^{-1})^2 + (2w_0T(1 - z^{-1})(1 + z^{-1}) + w_0^2QT^2(1 + z^{-1})^2} \tag{3}$$

From equation (3), the filter coefficients can be determined as:

$$a_0 = 4Q + 2w_0T + w_0^2QT^2;\ a_1 = 2w_0^2QT^2 - 8Q;\ a_2 = 4Q - 2w_0T + w_0^2QT^2$$
$$b_0 = 2w_0T;\ b_1 = 0;\ b_2 = -2w_0T$$

Finally, these equations are implemented inside *filterCoefs.h*, a function that receives a string identifying the type of filter (lowpass, highpass or bandpass, leveraging the calculation of these filter coefficients from previous work), a sampling rate, a cutoff frequency and a quality factor, and returns the calculations for every filter coefficient.

As for design choices, after having experimented with multiple combinations, subjectively judging the sonic output and also monitoring CPU load within Bela, we opted for a series of 10 bandpass filters (CPU load between 50% and 60%), each band of with a frequency range 500 Hz, with a quality factor of 50 (assigned by *gFilterQ[i] = 50.0* inside *setup()*).

Delay

For every delay line we created a buffer of size 88200 (two seconds with our sampling rate) and the correspondent write pointer. In order to apply different delay times to each filter output, in *setup()* we defined *gDelayInSamples[i]* to store integer multiples of the buffer size.

5.3 Real-Time Signal Processing

Insidre *render()*, for every n, there is a condition to check if the button is pressed, switching from 2020 and 2019 data. Given one of the datasets, an increment between previous and next data value is calculated, substituting the current data point by *gDataPoint += gDataPointIncrement*. Parameter mapping is then performed:

```
for(int i= 0; i < NUM_OF_DELAYFILTERS; i++){
gFilterFrequencies[i] = ::map(gDataPoint, gMinGlobal, gMaxGlobal,
                        536.71 + (500.0 *i), 36.71 + (500 * i));
gDelayFeedbackAmount[i] = ::map(gDataPoint, gMinGlobal, gMaxGlobal,
                          0.07 * (NUM_OF_DELAYFILTERS - i), 0.999);
gDelayAmount[i] = ::map(gDataPoint, gMinGlobal, gMaxGlobal,
                  0.1 , 0.3 * (NUM_OF_DELAYFILTERS - i));}
```

As described before, mappings control cutoff frequency inside every band (higher data values move the cutoff to lower frequencies), feedback amount of every delay line (higher values of data have higher values of feedback, progressively higher in the lower frequencies), and delay gain (higher data values have higher delay gain, progressively higher in the lower frequencies). This aims for a rendition that, given low pollution/NO2 levels, approximates the output to a 'clean' rendition of the piece, whilst high pollution/NO2 levels 'pollute' it with increasingly high amounts of the delayed signal.

Having obtained these parameters, every sample of our input signal is then read from a buffer (lines 196 to 199 in *render.cpp*, passed through the series of bandpass filters (lines 211 to 224), written into one of the delay buffers (lines 229 to 233) and summed to output (lines 236 to 245). In this last step, the final output of the delay lines is blended with the dry input, in order to maintain some temporal and contextual consistency of the original piece. Every step is commented out in detail on the file attached to this submission (also available at: `https://github.com/otnemrasordep/sonificationBela`).

6 Discussion

As is common in many sonification projects, this work was comprised of many design choices, ranging from source sonic material and data type selection, to specific features such as number of filter-delay lines and their technical parameters. Some of these decisions were driven by practical constraints (e.g. limitting the number of filter-delay lines to stabilize CPU usage) and others were conducted by experimentation and subjective listening evaluation (e.g. choice of quality factor, range of cutoff frequencies, delay parameters). Aesthetic decisions were carried out having in mind a balance between both the musical merits of the work and its ability to convey information. This effort of maintaining both artistic and scientific legitimacy is often referred as *the muddled middle* within the research field of sonification (Neuhoff 2019), often a root for debate amongst different researchers in the community, arguing about whether sonification should focus solely on the informational side or not.

Concerning evaluation of the output, subjective listening shows that it is easy to hear the differences between levels of air pollution throughout the piece (e.g. time frame *0:50* to *0:57* in the demonstration video, concerning values of 2019), and also that differences between 2020 and 2019 are noticeable (time frame *2:23* to *2:30*). After two listenings of the whole piece, one with the button held and the other without, it is possible to aurally perceive that 2020 presented lower levels of air pollution than 2019. From a sound design perspective, the audio effect applied produces pleasant, interesting results. Further experimentation (uncommenting line 191) led to also map data points to *gDelayInSamples[i]*. As is, due to the usage of circular buffers and the *modulo* expression, this yielded unexpected auditory results which deserve to be explored in future iterations of the work.

7 Conclusion

In conclusion, this report presents an implementation of a sonification of air pollution data using spectral delay. The system is able to aurally depict variations in air pollution levels in time, and also accounts for a comparison between distinct periods. The usage of bandpass filters with different delay lines proved to be a consistent solution and able to create interesting audio effects, allowing for a high degree of modularity and control.

Regarding future work, there's the intent of exploring the possibilities of turning this project into a sound installation. Possible paths include the implementation of a (*quasi*) real-time data fetching process and the addition of new forms of interacting with the system beyond the trivial button procedure (e.g. having both sonifications playing at the same time, panned left and right). Furthermore it would be interesting to enhance the audio effect by increasing the number of filter-delay lines, aiming for a more granular sonic output. As for scientific legitimacy, it is important that this work is subjected to a more thorough evaluation, not possible to be carried out during this assignment. To this extent, listening test with open end questionnaires are a possible choice. Asking participants to note the time frames that they think corresponds to worst pollution scenarios throughout the piece would also be a suitable test to assess this work's capability of conveying information.

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