Sonification as a means to generative music

By:

Ian Baxter

A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

The University of Sheffield
Faculty of Arts & Humanities
Department of Music

January 2020

Abstract

This thesis examines the use of sonification (the transformation of non-musical data into sound) as a means of creating generative music (algorithmic music which is evolving in real time and is of potentially infinite length).

It consists of a portfolio of ten works where the possibilities of sonification as a strategy for creating generative works is examined. As well as exploring the viability of sonification as a compositional strategy toward infinite work, each work in the portfolio aims to explore the notion of how artistic coherency between data and resulting sound is achieved – rejecting the notion that sonification for artistic means leads to the arbitrary linking of data and sound.

In the accompanying written commentary the definitions of sonification and generative music are considered, as both are somewhat contested terms requiring operationalisation to correctly contextualise my own work. Having arrived at these definitions each work in the portfolio is documented. For each work, the genesis of the work is considered, the technical composition and operation of the piece (a series of tutorial videos showing each work in operation supplements this section) and finally its position in the portfolio as a whole and relation to the research question is evaluated.

The body of work is considered as a whole in relation to the notion of artistic coherency. This is separated into two main themes: the relationship between the underlying nature of the data and the compositional scheme and the coherency between the data and the soundworld generated by each piece.

With the help of the mill I will make unending sounds from all sorts of instruments, which will sound for so long as the mill shall continue to move.

—Leonardo da Vinci

When new instruments will allow me to write music as I conceive it, taking the place of the linear counterpoint, the movement of soundmasses, of shifting planes, will be clearly perceived...The entire work will be a melodic totality. The entire work will flow as a river flows.

—Edgard Varèse, The Liberation of Sounds

This is not an eternity that begins at the end of time, but an eternity that is present in every moment. I am speaking of musical forms in which apparently no less is being undertaken than the explosion – yes – even more, the overcoming of the concept of duration.

—Stockhausen, Momentform

Our grandchildren will look at us in wonder and say: 'You mean you used to listen to exactly the same thing over and over again?'

—Brian Eno

I mean, pretty much all ambient music is major 7th chords, so harmony was going to be a big deal – how to approach harmony with this. Major 9th is also very popular: those are the two go-to harmonies in ambient music, if it isn't just a perfect 5th.

—Jim O'Rourke

Acknowledgements

This thesis is dedicated to all my music teachers.

I am grateful to the Julian Payne Tuition Scholarship for their contribution to my fees.

No undertaking of this size would be possible without the love and support of family and friends so thank you firstly to Alex for your love and understanding and to Billy, Jack and Ariane for keeping my feet on the ground and reminding me that some things are more important than music. To my parents Stuart and Gill for their unstinting support in all my musical endeavours. To all those friends and family who have acted as sounding boards and sat through my ramblings. To my supervisor Professor Adrian Moore, our supervision sessions have always sent me away with renewed enthusiasm for the task at hand and I will miss them dearly. To my technical gurus who have indulged with great humour and patience my queries about how I might actually make my ideas happen; to begin with Dr Dave Moore and latterly (soon to be Dr) James Surgenor whose gnomic utterances and koans (admittedly mostly “this would work better in SuperCollider”) have prompted many a revelation and change in direction. Finally, to Ben and Jenny for looking over my writing and their advice on putting my commas, hyphens and brackets right.

Table of Contents

Appendix: Portfolio of Works

Troy Ounce (2015)

Ephemeris de la Lune (2016)

Singing in the Wires (2017)

The Beach Buoys (2017)

Signing Wikipedia (2017)

Currency Wars (2017)

In Flight Music (2018)

Protest Songs (2018)

Notes from Underground (2019)

Squally Showers (2019)

Sonification Glossary

I was aware when writing that the terminology around sonification seems subject to some variation in spelling and usage. For avoidance of doubt this short glossary clarifies my use of terms throughout.

Sonification: (also plural sonifications) *noun* - used to mean both the technique and the product of that technique.
e.g. *Sonification* is the translation of data into sound
e.g. Sturm's Music from the Ocean is a *sonification* of sea buoy data
e.g. Quinn has carried out many *sonifications* of data

Sonifier: *noun* - a person carrying out a sonification.
e.g. The choices made by the *sonifier* influence the overall feel of the work
(n.b. My personal preference compared with sonifyer, which also appears in the literature)

Sonify: *verb* - to map data to sound
e.g. to *sonify* this phenomenon I applied a scheme where musical notes were mapped to…

Sonified: *simple past tense*
e.g. the data from buoys is *sonified* by Sturm in his piece…
also **Sonified** *past participle*
e.g. the *sonified* data is heard over several loudspeakers

Sonifying: *present participle* - a scheme has the effect of *sonifying* phenomena based on the data it represents
e.g. Adams' scheme has the effect of *sonifying* the Aurora Borealis above Fairbanks.

Sonifies: (*third person singular simple present*) - a scheme sonifies something based on the data it represents
e.g. John Cage's Reunion *sonifies* a chess game.

USB contents

Folder	**Title**	**Format**	**Duration**
video_tutorials/	beach_buoys_tutorial	.mp4 video	5' 08"
	currency_wars_tutorial	.mp4 video	8' 47"
	ephemeris_tutorial	.mp4 video	8' 09"
	in_flight_tutorial	.mp4 video	4' 02"
	notes_from_underground_tutorial	.mp4 video	5' 45"
	protest_songs_tutorial	.mp4 video	6' 48"
	singing_in_the_wires_tutorial	.mp4 video	5' 05"
	singing_wikipedia_tutorial	.mp4 video	11' 55"
	squally_showers_tutorial	.mp4 video	10' 44"
	troy_ounce_tutorial	.mp4 video	5' 15"
sample_recordings/	currency_wars_8_chan	.wav 8 channels	3' 34"
	ephemeris_de_la_lune_15-5-19	.wav Stereo	5' 15"
	sheffield_13-05-19_2_flights_evening	.wav Stereo	36' 51"
	frankfurt_13-05-19_2_flights_evening	.wav Stereo	5' 10"
	Barbican_1500_25-6-19	.wav Stereo	7' 33"
	Camden_Town_1545_25-6-19	.wav Stereo	4' 57"
	protest_songs_example_13-5-19	.wav Stereo	5' 07"
	singing_in_the_wires_08_05_2019	.wav Stereo	9' 49"
	singing_wikipedia_15-5-19	.wav Stereo	10' 06"
	squally_showers_stereo_1492019	.wav Stereo	4' 49"
	squally_showers_8_chan_1482019	.wav 8 channels	5' 50
	squally_showers_peek1482019	.wav Stereo	2' 30"
	the_beach_buoys_08-05-2019	.wav Stereo	2' 28"
	the_beach_buoys_15-9-2018	.wav Stereo	5' 01"
	troy_ounce_16-5-19	.wav Stereo	5' 56"
			Notes
portfolio_patches/	/currency_wars	.pd Pure Data patch and associated files	See readme.txt for running instructions and prerequisites
	/ephemeris_de_la_lune	.pd Pure Data patch and associated files	
	/in_flight_music	.py Python script patch, supercollider instrument and associated files	
	/notes_from_underground	.py Python script patch, supercollider instrument and associated files	
	/protest_songs	.pd Pure Data patch and associated files	
	/singing_in_the_wires	.pd Pure Data patch and associated files	
	/singing_wikipedia	.pd Pure Data patch and associated files	
	/squally_showers	.pd Pure Data patch and associated files	
	/the_beach_buoys	.pd Pure Data patch and associated files	
	/troy_ounce	.pd Pure Data patch and associated files	

1. Personal Motivation and Research Aims

I would like to begin with a reflection on my personal motivations for making the pieces in this portfolio and the research aims that developed from these motivations.

1.1 My practice

Attempting to describe as succinctly as possible my practice to a stranger I would say something along the lines of. “I’m a sound artist making works that consist of gradually changing sound, which use sonification of data as the basis for generative processes which generally don’t have a beginning, middle or end like conventional music does.”

Whilst this serves as a fairly accurate description of what I do, in one sentence I have pitched myself into several lively academic debates such as, *if you dispense with the beginning and end is it still music? And if you call what you do generative music, isn’t that just another name for algorithmic music? If the aim is to produce a musical piece using data, is it legitimate to use the term ‘sonification’ or should that be reserved for scientific, rather than artistic purposes?*

I welcome the challenge of making work at the intersection of such debates and presenting it in this portfolio, but before I go on to outline what others have said about those issues described above in the literature and arrive at some working definitions of generative music and sonification I want to cover how I got to this point and how my practice evolved. In other words: how did I arrive here producing a portfolio of works, and what questions am I seeking to answer?

1.2 From post-rock to generative music

My musical background is in pop music, playing various roles in several bands working in the guitar-based pop idiom. Home recording - at first with cassette based four-track machines, then computers, led me to a fascination with music made purely within the studio, particularly the ability to layer sounds. Increasingly, I became interested in writing intertwining guitar parts which rhythmically made use of '3 on 4' device where ostinati of differing lengths reconfigure themselves into different relationships as they are repeated[1]. I was intrigued by the chance harmonies and melodies that would emerge that I hadn’t necessarily intended, especially as multiple polyrhythmic lines were stacked up. These works were mostly made in the ‘post-rock’[2] idiom, which, whilst eschewing traditional lyric-based song forms, stuck to conventional rock

1 So, over twelve measures the '3' phrase is heard four times, overlapping the '4' phrase at different points which is heard three times at which point they come back into their first relationship.

2 Whilst definitions of post-rock vary I find Simon Reynolds formulation most useful. His definition was “Post-rock means using rock instrumentation for non-rock purposes, using guitars as facilitators of timbres and textures rather than riffs and power chords.” (Reynolds, 1994)

instrumentation (guitars, drums, keyboards).

Around 2001 I discovered Brian Eno and his records *Music for Airports* (1978) and *Discreet Music* (1975). As well as an attractive aesthetic which dispensed with the 'loud-quiet-loud' convention that dominated post-rock, I was also attracted to Eno's use of systems to produce his music. Eno's work using tape loops resulted in pieces that “create themselves” (Eno, 1994, para. 10) from a few short inputs – this felt preferable to laboriously overdubbing guitar parts.

A crucial element to the systems used to create *Ambient 1: Music for Airports*, was Eno's arrangement of the tape loops he used in a random manner, without explicit intention to create a certain compositional relationship between them (sticking to a defined pulse and its divisions). Instead of interlocking in rational relationships (i.e. the '3 on 4' device mentioned above), the tape loops were of arbitrary lengths that when played together would play out a series of “incommensurable” relationships that would never quite be the same unless the piece played for hours or even years as the number of loops increased. Eno explained in a 1996 lecture:

> Music for Airports, at least one of the pieces on there, is structurally very, very simple. There are sung notes, sung by three women and myself. One of the notes repeats every 23 1/2 seconds. It is in fact a long loop running around a series of tubular aluminium chairs in Conny Plank's studio. The next lowest loop repeats every 25 7/8 seconds or something like that. The third one every 29 15/16 seconds or something. What I mean is they all repeat in cycles that are called incommensurable -- they are not likely to come back into sync again. (Eno, 1996b, para. 16)

I was soon at a point where I was producing pastiches of Eno's work - by manipulating my tracker software to play a collection of looped samples, which, like Eno’s tape loops, would play in an incommensurable relationship. I worked with similar material to what I had previously, recording myself playing guitars, keyboards or trumpet, then setting these loops off to configure and reconfigure themselves. I would bounce down a 15-minute mix and put out a self-released CD-r.

1.3 No beginning, middle or end.

One element that Eno discussed intrigued me particularly; the idea that such music didn't have to be packaged and mixed down to 15 minutes (or anything up to the length of a CD). Rather, it could be set in motion and simply keep on playing. People could listen to as much or as little as they wished. In the notes to his most recent generative piece *Reflection* (2016) Eno reflects on the version released as an app (as opposed to the fixed version released on CD) and comments: "My original intention with Ambient music was to make endless music, music that would be there as long as you wanted it to be." (Eno, 2017, para. 7)

The idea that the piece is endless, constantly changing, without beginning, middle and end seemed a rich vein for musical exploration. However, one thing becomes clear: once you have stepped into this idea that the pieces you create are infinite there is a requirement for some kind of compositional strategy, system or algorithm (Collins, 2002). That is, given a potentially infinite timescale, it would be impossible for the composer to specify (in advance) the note-to-note details of a piece. The search for a compositional strategy (and a dissatisfaction with covering precisely the same ground as Eno) is part of the motivation for this portfolio of works.

As a specific strategy I felt I had soon exhausted the idea of incommensurable loops (not to mention the fact that this was simply aping Eno's approach). Although with computers (rather than loops of magnetic tape) the number of loops taken to baroque levels of complexity, an essential truth remains – as a listener, after one repetition of the material, you have quickly heard the complete content of a piece (the loops), even if their combinations are constantly changing. As Nick Collins observes about Jem Finer’s *Longplayer* (2000) which uses loops programmed to not repeat exactly for 1000 years: “Listen to *Longplayer* for a short while and you'll feel you know the sort of things it will do for the next thousand years, even though you can't predict its exact form at any one minute.” (Collins, 2002, para. 8)

Such process pieces can be characterised as deterministic – in other words, it is possible to ‘fast-forward’ the process (in relation to *Longplayer*, to play the piece starting at 2500AD, say), as its conditions are determined in advance. Likewise with Eno’s incommensurable loops, with the correct calculation, the position of the loops at any given point after they have been started could be determined.

1.4 Introducing chance

I became interested in strategies which incorporated an element of indeterminacy. In 2008, I was given the opportunity to make an installation in a gallery where I could explore making a piece that played for several hours. The piece was made up of pre-recorded incommensurable loops of guitar very much in the style I had been working in but it differed from my previous work in that it introduced an element of chance to define the pitch content of the loops.

This was rather naively along the lines of John Cage who (among other methods) used coin throwing and the I Ching (*Music of Changes*, 1951 and *Williams Mix*, 1952), imperfections in manuscript paper (*Music for Piano*, 1952) and star charts (*Etudes Australes*, 1975 and *Etudes Borealis,* 1981) to determine pitches, dynamics and other musical parameters. Setting aside the individual techniques employed by Cage for each piece, the unifying point is that something outside the composer's control is brought into the process of composing.

For Cage, this had the effect of producing an outcome that the composer could not foresee (Cage, 1961, p. 39). Put another way, it allows one to become both the composer and audience for a piece. There are several examples of artists discussing their works using sonification where the word 'surprise' is used. Stuart Jones (2012) refers to the element of surprise and the pleasure it brings to the composer (p. 298) and John Eacott (2012b) remarks on his piece Flood Tide "the computer reorganizes things and can produce surprises" (p.190). Rothenburg (2012) notes of John Luther Adams’ *The Place Where You Go to Listen* "You can never tell what nature is going to do. Adams as a composer can sit back and be endlessly surprised by what his piece is going to come up with" (p. 113). If not using the word surprise itself Eno picks up this theme of unpredictability when commenting on early generative experiments in an 1996 interview with Richard Williams: "'...it might make something quite beyond what you had imagined, something you didn't expect and couldn't predict.'" (Williams, 1996, para. 13)

The idea of chance and surprise stimulated my imagination as a means of creating more interesting work. Although the content of the piece was still determined by me (the sounds and instruments used), the structuring of the piece, in terms of which sounds were heard when and in what combination, was given away to an external agent. As a compositional strategy, this seemed well suited to producing works which were different each time they were played – being composed in 'real time', rather than (as discussed above) deterministic processes that were following a set path determined by the initial conditions (despite the long – near infinite - timescales they need to resolve).

1.5 Playing the weather

That 2008 piece was called 'Playing the Weather' (2008), a piece with pitches derived from a reading a newspaper weather report, assigning pitches to the names of the cities in the 'around the world' weather table, and moving through the report based on the reported temperatures. Using a chance element of this kind means there can be no pre-determination of what the piece would sound like on any given day.

The piece was literally worked out on paper: getting the weather report from that day's newspaper and following the system, noting down the pitches that resulted from the system, then recording the necessary loops to make the installation. Talking to a visitor to the exhibition about the relatively arduous process she remarked "why don't you get a computer to do the calculations and produce the loops?". This led me to pursuing study in the technological aspects required to make an electronic version of *Playing the Weather* (2013) (not following the same score, but proceeding along similar lines). The subsequent piece, completed as part of my masters studies and installed at the Birmingham Network Festival in 2013, accessed live data from the BBC Weather Observations Feed and translated it into a soundscape by parameter mapping. For example, higher temperatures caused a higher musical tempo, different conditions (rain, sunshine, snow) triggered different sounding sound files, visibility influenced the amount of reverberation applied, wind direction and speed caused sounds to move around an 8-channel space. This was my first successful experiment in producing a work where sounds generated began to reflect changes in the data in real time: an "endless and endlessly changing" piece of music (Eno's definition of generative music, Eno, 1996b) allied with an endless and endlessly changing stream of data[3] to drive it. This diverges from Cage's use of chance described above, which generally used chance to determine musical parameters that ended up in the production of a fixed work. The practice is closer to works such as *Reunion* (1968) which are indeterminate in performance (Pritchett (1993, p. 108) observes this distinction between chance and indeterminacy in Cage's works[4]).

3 Although not that endless, as it turned out, and far from infinite: changes in the format of the BBC data have rendered *Playing the Weather* inoperable and silent.

4 Although applying Pritchett's definitions, *Playing the Weather* fits somewhere in between the categories. It is indeterminate but most resembles Cage's chance techniques calculated in real time.

1.6 Towards my research questions

In creating and presenting this work there remained questions that spurred further investigation and have motivated my research interest since. Specifically to that piece: why weather data? Would anyone listening to the resulting soundscape on a given day, when it was raining, 8 degrees Celsius, with a north westerly wind at 5mph and so on be able to discern these details? Was my piece 'about' or representative of the weather? Were the mappings I arrived at (temperature to tempo, wind direction to spatial position) logical, or artistically defensible? In other words were artistic decisions implied in the data? e.g higher wind speed = greater panning speed. More generally: why any data? Would a generative system not be equally served (as many are) by simply seeding random numbers into the parameters, which are then modulated by some recursive process? This would after all produce the element of unpredictability and surprise that I (and others) have found so satisfactory.

A large body of artistic sonifications exist which have exploited data to drive musical processes[5] and whilst the works mentioned explore their datasets thoroughly, a fixed dataset produces a fixed, repeatable work. There are relatively few examples of works using live data to produce live sonifications[6] and even fewer explicitly link this to a definition of generative music as proposed by Brian Eno[7] (examined in section 2.2). The aim of this portfolio was to produce a body of works thoroughly examining how sonification of live data could be used as a means of creating generative music in various ways and to research effective strategies for mapping constantly changing data to constantly changing sound. My research question could be a simple as: Can sonification of data be used to create generative musical works? The trivial answer to that is ‘yes’ (see Croft, 2015). By pursuing the creation of a number of generative works the the aim becomes to discover whether, over the course of the portfolio, a general methodology for creating generative works via the means of sonification can been developed. Moreover, to explore in detail how a bespoke scheme for each set of live data can be adapted into an artistic scheme and final work within this general methodology. Finally, answering deeper questions of *how* sonification is a means to generative music and *why* the use of real-world data held my compositional interest over a whole portfolio of works - works which despite being derived from and inspired by external data sources manage to express my own compositional voice[8].

A further aim of this portfolio and thesis is to demonstrate that – contrary to arguments that have been made in relation to sonification for artistic purposes (see chapter 2 – particularly section 2.1.4) - artistic

5 See for example – although early works are somewhat contingent on the discussion of defining sonification in chapter 2 - Lucier (1965), Cage (1968), Sturm (2003), Dukich (2004), Quinn (2005), Saladin (2007), Foo (2015). Chen (2017), Van Ransbeeck (2019). The website sonifyer.org also keeps a list of musical sonification works (http://www.sonifyer.org/wissen/sonifikationmusik/) the majority of which are of fixed duration. The blog https://sonificationart.wordpress.com has similarly catalogued works of sonification art.

6 See for example Eacott (2008), Adams (2009), Parviainen (2017)

7 Of the three touchstone works I have chosen to look at in Chapter 2.3 only Eacott makes a reference to generative music.

8 See section 1.1 and my preference for gradually changing works, often involving continuous drones.

sonification schemes need not be arbitrary sets of data-to-sound mappings but schemes that are influenced by the data they aim to sonify and existing real world data sources that spark ideas for new artworks. As chapter 2 will go on to argue, this places my work in the context of supporting sonification theorists such as Cohen (1994), Gresham-Lancaster (2012) and Eacott (2009, 2011, 2012a, 2012b) and composers such as John Luther Adams who argue in favour of sonification as an artistic endeavour and against those authors (Polansky, 2002; Herman, 2008; Worrall, 2009; Scaletti, 2018) who wish to reserve the term sonification for exclusively scientific pursuits (although not denying or discouraging 'data driven music' as a separate an equally valid practice). To demonstrate the non-arbitrary nature of such artistic sonifications I want to investigate how, through decisions taken in the course of composition, an artistic coherence between data and artwork is achieved. This is partly achieved though looking at the perspective of other authors and composers in chapter 2, but primarily by setting out and analysing my own artistic processes in the pieces presented in my portfolio in chapter 3.

2. Some definitions

In the following chapter I will begin by setting out definitions for sonification and generative music. My intention is twofold: on a practical level these definitions allow me to expand and operationalise the terms set out in my title (sonification as a means to generative music). Both sonification and generative music have been the subject of some debate, and I feel it necessary, by reviewing these debates, to bring these contested terms into focus for the purposes of evaluating my portfolio of works. Secondly, a review of the literature places my work in the context of wider debates over the artistic use of sonification and whether generative music is a new form of expression, or simply a new term for an old practice (i.e. algorithmic music). With context-placing in mind the chapter concludes with a look at three exemplary pieces which have served as touchstones for my portfolio.

2.1 Defining Sonification

2.1.1 Basic Definitions

Definitions of sonification appear to coalesce around discussion of Kramer et al's formulation in The Sonification Report that, succinctly, sonification is “the use of non-speech audio to convey information.” (Kramer et al , 1999, p. 1).

Many authors start by quoting a version of this simple, direct definition (Worrall 2009, Walker and Nees, 2011, Eacott, 2011, Supper 2012, Vickers, 2016) and particularly the first sentence - as Worrall (2009) points out - “the first sentence of this 1999 definition appears to be the most widely used” (p. 312), although some authors add their own riders. Worrall (2009) quotes a fuller version of this formulation with some specificity added.

> [sonification is] the use of non-speech audio to convey information. More specifically, sonification is the transformation of data relation into perceived relations in an acoustic signal for the purposes of facilitating communication or interpretation” (p. 313)

De Campo (2007) also offers a slightly modified formulation, with slightly hedged phrasing, putting 'typically' into brackets:.

> Sonification or Data Sonification is the rendering of (typically scientific) data into (typically non-speech) sound designed for human auditory perception (para. 11)

In a more recent publication, Vickers (2016) whilst citing Kramer et al has his own formulation:

> Sonification is commonly described as the use of non-speech sound to convey information, typically through the mapping of data and data relations to properties of an acoustic signal (p. 135)

In this formulation, Vickers draws attention to the critical point of mapping of data – the decisions taken, in the course of making sound from data, although a problematic part of this definition for my purposes is the assumption that the sonifications must convey information (it raises questions of *what* information and the fidelity of its transmission in relation to the sonifier's original intention). Scaletti had also picked up on the idea of mapping being key, defining sonification as:

> a mapping of numerically represented relations in some domain under study to relations in an acoustic domain for the purpose of interpreting, understanding, or communicating relations in the domain under study…she further classified sonification mappings by level of directness: level 0) audification, level 1) parameter mapping, level 2) a mapping from one parameter to one or more other parameters. (Scaletti, 1994, quoted in Barrass and Vickers 2011, p. 147)

This definition also includes the notion that the purpose of sonifications is to communicate information (with the associated problems pointed out above). More significantly, Scaletti's definition also introduces the idea of how *direct* a sonification is and the characterising or categorising of sonifications by their 'order'(roughly a measure of how directly related to the original data they are): this theme will be picked up later.

Hermann (2010) distils his thoughts into a one sentence definition, seeking to reserve the term sonification for its scientific purposes: "Sonification is the data-dependent generation of sound, if the transformation is systematic, objective and reproducible, so that it can be used as scientific method." (para. 3). He focuses not on the communicative proprieties (not mentioning the conveyance of information) but on the systematic, objective and reproducible generation of sound from data (making it scientific in method).

The above definitions are broadly representative of the views of the auditory display community, those who define sonification as an alternative method for communicating data analogous to the established use of visual displays (e.g bar charts or scatterplots). Elsewhere in the literature, away from the specific corpus that exits around this community, more general definitions of sonification can be found. Doornbusch (2009) states, for example, "the practice of generating sound, or music from data sets is called sonification" (p. 76) (a broad definition that potentially brings [some of] John Cage's chance operations, and Xenakis' application of statistics among others into its net) . Such a general definition is useful in my context as it contrasts with the locked-down specifics of Herman and allows in artistic, or musical sonifications; although it requires the qualification, I feel, that the datasets in question must be non-musical, otherwise such radical reduction would lead us to say all digital music is a sonification. An digital audio file of *Bohemian Rhapsody* is, after all, a set of binary data, one which, when decoded and played at the correct sample rate and so on, is transformed into the song we can hear. Arguably, a working definition of sonification must contain the germ of transformation from a non-musical (or non-audio) source data, to an audible result. This conclusion has also been reached by Stene and Akiyama (2009) who define or frame sonification as "the transformation of *non-sonic data* [emphasis added] into audible sound " (p.545). Similarly, Parkinson and Tanaka (2014) state "sonification is, at its most basic, the conversion of something from a *non-sound medium* into sound [emphasis added]". (p. 151). Van Ransbeeck (2018) places sonification as a subset of algorithmic music (p. 156) and concludes "Sonification art is an arts practice that uses data from *observations of world phenomena* [emphasis added], which are mapped onto musical parameters...and that uses sound to manifest itself." (p. 157).

2.1.2 Taxonomy of sonification methods

Moving away from attempts to capture sonification in a single sentence, another approach to arriving at a definition is to look at the various practices that make up sonification. Walker and Nees (2011) discerned three broad areas of sonification activity:

Audification: where the sonified data are brought directly into the audio domain through the direct translation of a data waveform into sound (Kramer, 2004, quoted in Dombois and Eckel 2011). For example, the playing of earthquake seismographs as audio (with some transposition to bring them into the audio range) or medical electroencephalogram (EEG) data. This relies on a dataset collected having sufficient a sampling rate to enable direct translation as playable digital waveform.

Model-based sonification: where user interactions drive a model and the user data generated translates to an excitation of that model. Hermann (2011) explains:

> Model-Based Sonification demands the creation of processes that involve the data in a systematic way, and that are capable of evolving in time to generate an acoustic signal....Sonification models remain typically silent in the absence of excitation, and start to change according to their dynamics only when a user interacts with them. The acoustic response, or sonification, is directly linked to the temporal evolution of the model. (p. 399)

Parameter Mapping (or 'PMSon'): where parameters in the data are mapped to parameters in the resulting sound: pitch, rhythm, tempo, timbre, any variable within what Harper has termed the "music space" (Harper, 2011, p.80). In an oft cited example, the Geiger counter maps the level of radiation to an audible click, and the higher the radiation the closer the clicks come together (in musical terms, the tempo increases). Parameter mapping has the advantage over audification that the data does not have to be sampled at an audio rate. Instead it provides 'control' data (which can be scaled) for the sonification scheme devised by the sonifier. The ubiquity of numbers in digital music production to represent such control parameters (where notes can be expressed as MIDI note values, or frequency in hertz, stereo panning as -1 (left) to 1 (right)) make for an easy fit – with some scaling – to most data. It is for perhaps this reason that parameter mapping appears to have the strongest relationship with musical sonifications. Although not exhaustive, Sonifyer.org lists some 39 compositions using parameter mapping, vs 11 using audification. This is, perhaps, because parameter mapping sonification (unlike audification) gives the composer a free hand to map their sounds (created through synthesis, or from existing sound in the *music concréte* tradition) to the data. The scrutiny of the mapping scheme employed and its relation to the underlying data are the key part of the analysis of my works in section 4, where evidence of the composer's hand is evident.

Gresham-Lancaster and Sinclair (2012) add a further category of 'ReMapping' to this taxonomy (although it is arguably a sub-category of parameter mapping) where a familiar sound source is 'perturbed' (changed in some way) by a flow of data. For Gresham-Lancaster and Sinclair, ReMapping is distinct in its use of already familiar acoustic signals – i.e. music. Where parameter mapping may use quite abstract sounds – a bleep from a signal generator's tempo altered by heart rate, say, a ReMapping may involve altering the tempo of a samba beat.

2.1.3 Some analytical tools: the analogic-symbolic continuum, indexicality, first and second order sonifications

Going further beyond simple one-sentence definitions of sonification and their classification, the literature around sonification provides several useful analytical models. Some of these prove useful in trying to untangle artistic sonification from other uses of the term and are also useful analytical tools when it comes to considering my own works in relation to my research questions.

Kramer (1994) draws a continuum between analogic and symbolic sonification. At the analogic end there is “an immediate and intrinsic correspondence between the sort of structure being represented and the representation medium” (p.21). He cites how the Geiger counter's “increases and decreases in the acoustic signal are a simple analog of increases and decreases in radiation” (p. 21). A symbolic mapping on the other hand, takes a discrete sound and links it to some data “a user login to a computer causes a door knocking sound” (p. 23). In Kramer's continuum, parameter mapping straddles analogic and symbolic. The placement of any one parameter mapping sonification on the continuum is largely down to the mappings and sounds used.

In a similar vein to the analogic/symbolic continuum, Vickers and Hogg (2006) and later Barrass and Vickers (2011) outline the concept of 'indexicality', a term borrowed from visualization. High indexicality is exhibited in sonifications where “the sound is derived directly from the data (for example, through the use of direct data-to-sound mappings)” (p. 157). Low indexicality arises “from more symbolic or interpretative mappings.” (Barrass and Vickers, 2011, p. 157). They state, “In sonification practice indexicality becomes a measure of the arbitrariness of a mapping” (Barrass and Vickers, 2011, p. 157) . It is in the arbitrariness (or perceived arbitrariness) of some mapping schemes that some find fault with artistic sonifications; what is gained in artistic expression is traded off against the relationship between data and sound. Returning again to my research questions, in investigating what I have called artistic coherence, it could be considered that it is the arbitrariness (or rather, lack, thereof) in a mapping scheme that is being questioned and analysed. I am attempting to argue that the sonification scheme is not arbitrary and has been tailored to the underlying data in a process of artistic exploration (arriving at a 'coherent' result).

The notion of 'closeness' of resulting sound to data, resembling the indexicality described above, has been taken up by those authors who have spoken about levels (Scaletti, 1994) or orders (Gresham-Lancaster, 2012) of sonification. Gresham-Lancaster (2012) outlines first-order sonifications as:

> ...the direct linkage process between the data itself and some technique for rendering it in a sound space. The data set is linked on a one-to-one mapping. Notes or pitches, filter openings, changes in a physical model parameters or any one of hundreds of techniques that are directly drivers of perceptible changes in the sound. A number goes up and the assigned parameter is increased proportionally. A number goes down and the assigned parameter is decreased proportionally. (p.210)

Whilst acknowledging the skill that goes into devising such sonification schemes Gresham-Lancaster (2012) cites, “a lack of expressive nuance in being this literal with the remapping of data set to acoustic properties”

(p. 210) as a key problem in terms of the aesthetic dimension of such sonifications. Put another way, aesthetic considerations such as whether a piece is pleasant to listen to and engaging for the listener (although it has to be admitted these are to some extent in the ear of the beholder) are traded off for high indexicality, i.e. as close as one-to-one mapping of the data as possible. By contrast second-order sonifications allow more nuance to be introduced into a sonification scheme through “an intermediary set of conceptual frames” (Gresham-Lancaster, 2012, p. 210). He notes:

> Second-order sonification is the application of time bound algorithmic processes that are driven by sets or clusters of a data set. This can give the designer an option for more culturally bound decisions that can frame the output in larger musically formal structures. (Gresham-Lancaster, 2012, p. 210)

In other words, a second-order sonification uses reference points (genre, style, existing musical conventions) as part of its makeup. He goes on:

> Many current sonification algorithms are just doing the primary first-order type of processing, converting data directly into some audio parameter. In a simple case, a set of numbers are ranged and scaled and the resultant array is played back as a series of melodic notes, for example. However, as more sophisticated algorithms are brought into play, other elements that are musical in nature and not directly tied to the actual sonification can be introduced. In this example case, decisions regarding what pitch sets are used (i.e., scale and/or gamut) and rhythmic mappings. While these sorts of decisions are outside of the direct sonification, they can be very important in framing the sonified data in a context that is still apparent to the listener, but carries an element of musical style that conveys a more harmonic and culturally familiar result.” (Gresham-Lancaster, 2012, p. 211)

In working in second-order, it could be said that some indexicality is traded off for a more artistically satisfying result. In section 2.3, where I discuss some exemplary works that have influenced my own investigations, working in the second-order is a vital component.

Consider an example of pitch and a theoretical sonification based on continuously changing temperature from a weather station. Working at the analogic end of Kramer's continuum, I would argue that for a coherent relationship between data and sound, a rise in temperature would equal a rise in pitch (as opposed to a symbolic mapping, say, of an alarm sound sounding as the temperature exceeded a previous high or low). If I were working toward high indexicality I may link the temperature and pitch directly, so an increase of one degree centigrade equals an increase of 1Hz in an oscillator. The range of temperatures in my garden may only be roughly -5 on the very coldest winter days, to maybe 30 on a hot summer day. I may not therefore perceive much change in pitch, even over a year's worth of data, by mapping the Celsius and hertz values directly. I may choose to map linear temperature data to logarithmic pitch values, losing a little indexicality and resulting in a non-musical glissando, still in the first-order as described by Gresham-Lancaster, and as hinted at by him, not something that would necessarily be very satisfying to listen to. Some indexicality is further lost if I decide to make changes in temperature step through an existing musical scale. I am now working in the second-order, introducing a recognisable musical element that is nevertheless driven by the underlying data (lower notes = lower temperature).

2.1.4 Sonification or data driven art?

The trade-offs between indexicality and artistic interpretation are at the heart of a debate that has "simmered" (Vickers, 2016) since the first attempts to define the practice and field of sonification were first outlined at the international conference for auditory display (ICAD). Polansky (2002), Herman (2008), Worrall (2009) and Scaletti (2018) have questioned whether sonification used for musical and compositional purposes (with the purpose of conveying information downgraded in preference of achieving an artistic result) undermines, invalidates, or even prohibits the use of the term sonification. Inevitably it is into this debate that this thesis and portfolio of works is cast. I will begin by summarising the positions on either side although the title and premise of this thesis probably reveals my position in advance (I argue in favour of determining all (non-musical) data to sound practice as sonification).

In outlining some of the functions of sonification, Walker and Nees (2011) include art as a category noting "data sets can be used as the basis for musical compositions." (Walker and Nees, 2011, p. 15) but "While the composers often attempt to convey something to the listener through these sonifications, it is not for the pure purpose of information delivery." (Walker and Nees, 2011, p. 15)

This theme is picked up by authors (Herman 2010, 2008, Worrall 2009, Scaletti, 2018) who appear to want to draw a sharp dividing line between the scientific, information-displaying function of sonification and the use (or abuse) of data to drive compositional schemes, or deny the existence of "artistic sonification" altogether (Supper, 2012, p.253).

Hermann (2008) draws an analogy with visualisation in relation to painting:

> Another challenge for the definition comes from the use of sonification in the arts and music: recently more and more artists incorporate methods from sonification in their work. What implications does this have for the term sonification? Think of scientific visualization vs. art: what is the difference between a painting and a modern visualization? Both are certainly organized colors on a surface, both may have aesthetic qualities, yet they operate on a completely different level: the painting is viewed for different layers of interpretation than the visualization. The visualization is expected to have a precise connection to the underlying data, else it would be useless for the process of interpreting the data. In viewing the painting, however, the focus is set more on whether the observer is being touched by it or what interpretation the painter wants to inspire than what can be learnt about the underlying data. Analogies between sonification and music are close-by. Although music and sonification are both organized sound, and sonifications can sound like music and vice versa, and certainly sonifications can be 'heard as' music…there are important differences which are so far not manifest in the definition of sonification (para. 7)

He goes on to outline a utilitarian definition of sonification that "emphasizes important prerequisites for the scientific utility of sonification" (Hermann, 2008, para. 10):

> [Sonification] Definition: A technique that uses data as input, and generates sound signals (eventually in response to optional additional excitation or triggering) may be called sonification, if and only if:
>
> (C1) The sound reflects objective properties or relations in the input data.
>
> (C2) The transformation is systematic. This means that there is a precise definition provided of how the data (and optional interactions) cause the sound to change.
>
> (C3) The sonification is reproducible: given the same data and identical interactions (or triggers) the resulting sound has to be structurally identical.
>
> (C4) The system can intentionally be used with different data, and also be used in repetition with the same data. (Hermann, 2008, para. 9)

He explains why conditions 3 and 4 are violated by many ‘musical’ sonifications

> Obviously there are many examples where data are used to drive aspects of musical performances, e.g. data collected from motion tracking or biosensors attached to a performer. This is, concerning the involved techniques and implementations similar to mapping sonifications. However, a closer look at our proposed definition shows that often the condition for the transformation to be systematic C2 is violated and the exact rules are not made explicit. But without making the relationship explicit, the listener cannot use the sound to understand the underlying data better. In addition, condition C4 may often be violated. If sonification-like techniques are employed to obtain a specific musical or acoustic effect without transparency between the used data and details of the sonification techniques, it might, for the sake of clarity, better be denoted as ‘data-inspired music’, or ‘data-controlled music’ than as sonification. Iannis Xenakis, for instance, did not even want the listener to be aware of the data source nor the rules of sound generation. (Hermann, 2008, para. 30)

Herman’s utilitarian approach is evident both in placing emphasis on utility for the listener (the listener using the sound to understand the data) and the artists' intentions for their use of data (citing Xenakis) not being interested in the listener being aware that Gaussian distributions, Game Theory, and so on were the genesis of the piece[1]. Hermann’s use of the phrase “*without transparency* [emphasis added] between the used data and details of the sonification techniques ” (Hermann, 2008, para. 30) brings us back to a definition of sonification that foregrounds the information-carrying function of sound. A true, accurate or successful sonification, for Hermann, therefore, is one where the message it is *intended* to convey reliably is received and understood by the audience.

If music driven by data is not a sonification, what is it? Worrall (2009) uses the term ‘Data Music’ This echoes Hermann's (2008) observation that some artistic sonifications,”might, for the sake of clarity, better be denoted as ‘data-inspired music’, or ‘data-controlled music’ than as sonification.” (Herman, 2008, para. 30). Worrall places such 'Data Music' in a perceptual continuum (2009, p. 329), where at one end there are works which have 'representational' mapping of data to sound (meeting Hermann’s (2008) conditions above) and at the other end of the spectrum there are works where the data is transformed freely by the sonifier. Worrall observes that in contrast to sonifications which map their data representatively, “Close to the “free data” end would be data music that uses arbitrarily formatted digital documents as control data for some sound synthesis routines as *arbitrarily determined by the sonifier* [emphasis added]” (Worrall, 2009, p. 329).

This characterisation of data music as using ‘arbitrarily formatted’ and 'misappropriated' data (Whitelaw, 2004) is an earlier precursor to the notion of ‘transparency’ that Hermann developed in his critique of non-scientific sonifications. Whitelaw (citing the process of 'data bending' – appropriating data contained in digital documents as raw sound) argues “In one sense sonification is the converse of data bending: where data bending is arbitrary, abstract and aesthetic, *sonification is designed, referential and functional* [emphasis added]” (Whitelaw, 2004, p.50).

Polansky (2002) proposed that scientific and artistic sonification be separated into two subsets of auditory display. Artistic practices should be termed 'manifestation' (reserving sonification for scientific approaches): “When the intent is clearly to use a formal or mathematical/formal process to create a new musical idea as a form of sonification, I propose the term manifestation”. (Polansky, 2002, para. 9). In this

1 Although if Xenakis were so keen for the listener to be unaware of his process, it prompts a question as to why he wrote his book Formalized Music (1992) which sets out, in great detail, his application of mathematics in composition.

terminology a piece such as Xenakis' *Duel* (1959) is a manifestation of game theory. More recently, along similar lines, Scaletti (2018) has suggested that the term sonification is reserved for scientific uses and data-driven music for musical application. Scaletti argues that this benefits scientific sonifiers by freeing their audience from the expectation of a musical experience (and in turn that they will listen carefully for the meanings that the sonification is trying to convey) and for composers in that they are freed from the expectation that the music is somehow instructive or illustrative of the underlying data being sonified (p. 379). For Scaletti, the continued use of sonification in a musical context prevents it from being taken seriously as a scientific method (p. 379).

Gresham-Lancaster (2012) welcomes Hermann’s attempt to accurately capture a definition but cautions against the emphasis on the scientific aspect of sonification alone. He seeks to draw a boundary which is inclusive of all work which is based on converting time based data streams: “Work that is not truly based on the conversion of time based data streams realized into audio should not be mistakenly called sonification but equally framing it in terms of 'scientific method' is also as grave a mistake” (Gresham-Lancaster, 2012, p. 207) .

In 2006 Vickers and Hogg attempted to cut through the music and sonification debate, stating that music and sonification are actually equivalent, and “whether we hear a sonification or a piece of music is simply a matter of perspective.” (Vickers and Hogg, 2006, para. 22). They describe sonifications as existing in an aesthetic space between the concrete and abstract, ars musica and ars informatica. Various pieces of sonification (or music, data driven music) can be placed in this space, which is circular rather than a continuum. In one example they note the similarity between a work designed as a sonification, and the work of a sound artist:

> Hayward’s frequency doubling of seismographic data is analogous to the work of Hildegard Westerkamp who slows down environmental sounds to extract their previously unheard musical characteristics. They both manipulate the speed of the data but the intended outcomes are different.” (Vickers and Hogg, 2006, para. 19)

This sense of differing perspective was picked up by Cohen (1994) in a much earlier paper. Cohen discusses John Cage's *Music of Changes* and *Reunion,* describing Cage as the “spiritual father of auditory display” (p. 503). He goes on to stake a claim that Cage's *Music of Changes* is in fact a parameter mapping sonification:

> The method of composition Music of Changes seems strikingly familiar – the “data” were generated from the results of coin tosses, an mapped to pitch, duration, amplitude and timbre of sound...Scaletti [speaking at ICAD, October 23, 1992] and Kramer [personal communication], both suggest that Cage did not compose Music of Changes or Reunion with the intent to communicate the underlying data structures...*However, intent is in the ear of the beholder, not just in the mind of the creator, one may listen to a sound for either its musical quality or its informational value...one could imagine mentally attempting to position chess pieces whilst listening to Reunion* [emphasis added] (Cohen, 1994, p. 504)

This conceptualisation of intent contrasts with Hermann's above. Who is to say if the intended message of a sonification has been conveyed or what the intended message is? Vickers and Alty (2006) describe Cage's intentions as “moot”

> Whether Cage intended to communicate information regarding data sets by music or merely used data as a mechanism for the creation of new music (i.e., was the music a by-product or the intentional product) is moot; what is interesting is that Cage believed the relationship between music and data could be exploited (Vickers and Alty, 2006, p. 339)

Building on his previous writings Vickers (2016) makes a further attempt to address the issue of sonification and its relationship to music comprehensively and to address the simmering debate referred to earlier, one that goes back to the first ICAD conference. He writes "Since then [the first ICAD conference] there has been an increasing number of musical and sonic art compositions driven by data of natural phenomena, *some of which are claimed by their authors to be sonifications*" [emphasis added] (Vickers, 2016, p. 135) and sets out the problem thus:

> composers engaging in sonification music will often lose sight of that goal [communicating data] altogether in pursuit of aesthetic interest...there is a tendency for some composers to use sonification as a label even though the music does not communicate information about the data (Vickers, 2016, p. 140)

He describes a piece sonifying NASA data as musically impressive but not admitting the sort of inspection of the data that is the goal of sonification (Vickers, 2016, p. 140). I find this characterisation problematic, as, like Hermann (2008) it appears to want to reserve the term sonification (as a noun) for those pieces which successfully communicate information from data. Yet as Cohen (1994) argued, who is anyone to say exactly what an artist intended to communicate through their sonification?

Gresham-Lancaster (2012) frames the debate thus:

> Direct usages of data sets as a compositional determinate that yield the most musically satisfying results are rarely the most transparent or obvious. So, here is a tangible problem in the field. If there is not an exact and tangible congruence between the rather tenuous semiotic link made by the researcher between a given data set and the resulting sonification by an arbitrary listener, does this negate the validity of that sonification? Or more simply, if the listener does not understand some relationship between the sonification and the data set, is the work successful? (p 208)

Gresham-Lancaster is here approaching two terms that I have used also – he talks of a musically satisfying result (although 'satisfying' is not without its semantic problems – satisfying to whom?) and a "tangible congruence" between a data set and the resulting sonification. This 'satisfying and tangible congruence' anticipates what I've termed this artistic coherence in section 1.6. I feel this is a useful approach, to focus on whether there is a strong congruence between data and sounds heard, whether high indexicality is being sought for the purposes of scientific inquiry or whether a sonifier has more artistic intentions.

Such artistic intentions need not always be described as moot. Indeed, many artists are willing to state their intentions quite explicitly (see AI & Society Volume 27, Issue 2, where artist statements are included as a matter of course). In an example of one of these artist statements, John Eacott sets out the intentions behind his piece Flood Tide:

> The work is a kind of sonification although in the context of this journal that term requires qualification perhaps. If my intention was to represent the changes in tidal flow as clearly as possible, I would not choose to use 40 musicians. My aim is to make a musical performance, which is generated by tidal flow. To let the audience experience, an earthly process that is taking place, regardless of whether it is being sonified or not. The work acts as a kind of intervention with nature and a shift in perspective. To make sonic what is normally without sound." (Eacott, 2012a, p. 287)

Returning to *Reunion* (1968) by John Cage (which can be described as a sonification of a chess game) where moves on a chess board drive a mix of sound, sending it to different places around the auditorium as the pieces are moved: if we assume a level of technical skill possessed by an audience member in holding the position of all the pieces in their mind at any one time, could they really visualise the progress of the game in their head from the sounds alone? As no specific sound is assigned to each piece, or square on the board, one might argue that this sonification performs rather poorly in conveying the state of the game at any one time. Even a skilled audience member may be unable to follow the moves precisely and will not gasp as Cage makes a foolish or surprising move (placing his queen at risk of capture, for example).

But does this mean Cage's piece is a failure of sonification? As the scientific sonification argument would have it (Hermann et al), in the hypothetical example the information has not been clearly conveyed to the audience. Perhaps it is worth considering what *is* conveyed by Cage's scheme. Given its means of operation where pieces block out photocells placed in the board, the amount of material left on the board (governed by the number of captures in the game) affects the amount of sound heard in the auditorium. The designer of the chess board, Lowell Cross, explains “the complexity of the sound environment enveloping the audience increased as the early part of the game progressed; it then diminished as fewer and fewer pieces were left on the board” (Cross, 1999, p. 38).

Each move of the game involves a change in the sounds heard. The audience get an impression that something has happened in the game. If Cage's intent was to sonify the rhythm of a chess game, rather than its exact details, then he has been successful. In Gresham-Lancaster's terms above there is an “exact and tangible congruence” between the chess game happening in time and the sounds heard. Furthermore, Cage's piece could be considered what Lefebrve (1992) termed rhythmanalysis; the study and bringing to light of the hidden rhythms of everyday life. (Sonification and its connection to rhythmanalysis is also made by Palmer and Jones (2011) and it is a concept I will return to.)

Given the tide of artistic uses of sonification, it seems the trend toward trying to draw a boundary between data music and sonification seems a rather Canute-like endeavour; far better a pragmatic framework that accepts that sonification is being used (rather than appropriated (Vickers 2016)) as an artistic technique and to criticise such artworks not for transgressing a definitional line but on whether they are successful in their aesthetic goals. Such a view sees sonification more as a verb than a noun, a technique to be used, rather than a thing to be arrived at. Gresham-Lancaster (2012) sums up:

> The real craft of sonification is to meet the requirements of authentic data representation in a more universally acceptable and hence very musical context. There are many easy to use digital tools available now that afford any interested ‘‘sonifier’’ the ability to remap some set of parameters from a data set and tie it to an acoustic parameter. Filter and oscillator frequency, amplitude and reverb amount can all be directly tied to a synthesis patch. With that, you have a true sonification that meets the criteria of being in the scope of ‘‘scientific method.’’ *The real challenge comes when musical artistry and an awareness of style, form and expression are integrated with these processes.* [emphasis added] (p. 210)

The idea of a 'challenge' is echoed by Johnstone (2013):

> Here is the challenge for sonification. To what extent can sounds that emerge from a stream of code be more than utilitarian? To what extent can sonification effect an aesthetic transmutation, allowing for engagement with sound and source together? Finally, to what extent can it be a potent artistic experience? (p.193)

Many artists have lined up to address this challenge, creating “A rich tradition, especially within the domains of contemporary classical music and sound art, of transforming data into sound for musical purposes” (Supper, 2012, p. 253). As Schoon and Dombois (2009) observe and document, “The ‘sonification-based music’ genre has now been growing for some years within the field of sound art” (para.

14). Setting the scene in an editorial to a whole issue of the journal Organised Sound dedicated to sonification, Schedel and Worrall (2014) state, "Sonification can be used for purely scientific purposes, or as the basis for musical composition" (p. 1). Supper (2014) focuses on the use of sonification and reception of sonification in the public domain by scientists and artists (rather than in the specialist auditory display research community), characterising the line between sonification as a scientific tool and sonification as a means of artistic expression as 'blurry' (Supper, 2014, p. 36). This echoes Barrass' and Vickers' (2011) contention that any wall between sonic art and auditory display is a false one (p. 165).

McKinney and Renaud (2011) cite a history of composers using sonification and set their position out as follows:

> Sonification is often understood to be a scientific activity, primarily aimed at finding another means for understanding a complex data set…many composers have approached sonification as a more artistic activity, not necessarily devoted to attempting to provide purely intellectual clarity to a data set, but instead using it as a musical resource to drive a composition....Early examples of this include Reunion by John Cage, which uses a chess board as an audio mixer, and Music for Solo Performer by Alvin Lucier, which involves amplifying brainwaves to the point of acoustically activating percussion instruments. Marty Quinn investigates sonification of natural forces in multiple works, including The Climate Symphony which generates gamelan-esque rhythmic music based on the pulsating climatological history of the earth, and Rain, which converts the intensity of ice melting over time into pitch and rhythm for percussive sounds. Bob Sturm uses the undulations of the ocean's waves in his piece Music from the Ocean to drive electronic music creating 34 different data mappings to produce individuals musical tracks (para. 10)

John Eacott (2011) is unapologetic about creating data driven compositions (*Flood Tide* and *Hour Angle*) and calling the process sonification:

> If the purpose of a sonification is to represent data there are simpler, clearer and cheaper ways to do it than using, in our case, live musicians. To put it another way, these sonification pieces are built on an assumption that there is a value in representing data as music rather than sound…Another reason to make music by sonifying data is simply because we can. Sonification is a further example of an art form that has been opened up by advances in computer technology. It is a means of contemporary cultural expression. Our use of sonification is as a form of artistic expression and musical composition. In other words we take data and convert it into - or present it as - music. (p. 70)

Along similar lines Johnstone (2013) declares "Artistic sonification naturally engages in the discussion of sound and aesthetics...The author's approach focuses on the natural beauty inherent in the data; the regular rhythms of tides; temperatures and seasons... (p.192). John Luther Adams (2009) does not get tied up in conceptual knots over whether what he is doing is a sonification[2] or not. He simply uses the technique. He explains:

> In *The Place,* streams of data tracing natural phenomena…are transformed into sound through a process that is sometimes called *sonification*. Sonification is not to be confused with audification, which is the direct rendering of digital data with inaudible frequencies into the audible range, using re-sampling…Sonification is the process of mapping data with *some other meaning* into sound. (p. 133)

Roads (2015) gives the last word to Stockhausen who points out the difference between a scientific sonification and music composition:

> Of course [the demonstration of a sound splitting into six parts in *Kontakte*] could be done more or less intelligently...A physics professor would just have gone down six and a half octaves, and leave it at that. Someone else might just, well, vary it a little, make it a bit more inventive. If the same process is composed by different people and one is more imaginative than the other, then that's all there is to say about the process, and about the difference between a physics professor and a composer in this context (Stockhausen quoted in Roads, 2015, p. 323)

Reflecting on this, Roads concludes that today the lines between artistic and scientific projections are blurred (p. 323).

2 Although he is writing for the general reader, Adams makes a mistake of equating parameter mapping sonification with sonification itself. Parameter mapping and audification are better considered to be sub-techniques of sonification as a whole (see Walker and Nees, 2011)

2.1.5 Artistic Themes I: A question of honour; being "true to the data"

The question remains: if artistic sonification is not aiming at a highly indexed, highly accurate picture of the data fit for scientific interpretation, what is the aim of artistic sonifications? At a simple level, as I outlined in section 1.4 discussing my own practice, part of the attraction of using data is the introduction of unpredictability and chance. Supper (2014) captures this idea, placing sonification in a broader artistic trend of "eliminating artist's ego or personality from the artistic product" (Supper, 2014, p. 39 citing Morgan 1998). Composers engaging in sonification are "ostensibly handing over some compositional decisions to scientific data rather than an individual artist" (Supper, 2014, p.39) freeing themselves from the "overindulgences of artistic romanticism" (Supper, 2014, p. 39 citing John Luther Adams). Critics are apt to ask, "why this data? Why *any* data – why not just random numbers?". A theme that emerges in the literature around artistic sonification is the notion of being 'true to the data'. In her discussion of John Luther Adams' *The Place Where You Go to Listen* (2009) Supper argues that being 'true to the data' is often more important for artists who work with sonification than it is for scientists using the same techniques (Supper, 2014, p.38). She expands:

> it is not surprising that meddling with or massaging the data is often more frowned upon among artists working with sonification than among scientists using it for the purposes of popular outreach: deliberately manipulating the sounds resulting from the sonifications, or picking only those sounds that are especially beautiful, goes against the very concept that sonification embodies for such artists (Supper, 2014, p. 40)

Allied to being true to the data is being true to the subject of the sonification:

> The sonification, for instance, of a volcano is different from the sounds that are emitted by the volcano itself. However, certain rhetorical, musical and technological strategies are used to suggest that the sonification represents something about the volcano that might not be immediately visible or audible from the volcano, but from deeper within it. It is not about sounding like a volcano per se, but about being true to the volcano – or rather, about allowing listeners to believe that the sonification is true to the volcano (Supper, 2014, p.51)

What Supper (2014) describes is the concern of artists that a work resulting from sonification 'makes sense' [my phrasing] or in other words that people can hear the relationship between data and the composition (a change in data results in a change in sounds heard) and that their composition incorporating data is somehow *representative* of the data. Also picking up on a theme of 'truth' Gresham-Lancaster (2012) argues that the audience of a sonification must *trust* what they are hearing is an actual representation of the data even if the representation itself is quite abstract (exhibiting low indexicality, as Barras and Vickers (2011) would have it).

> When successful, a sonification in the form of abstract numeration creates something tangible, a direct experience of the sonification of that data…. It is absolutely imperative that this trust is present and that the material that is represented as a sonification is genuinely generated directly from the data being sonically examined. However, I do not believe that this means that the perceptual linkage needs to be obvious or even apparent. (Gresham-Lancaster, 2012, p. 208)

Along similar linguistic lines, the idea of 'honouring' the subject was put forward in an article regarding the sonification of Kepler's Music of the Spheres[3]: "Professors Ruff and Rodgers are proud not only to have made Kepler's music audible, but also to have *honoured* him as well." [emphasis added] (Bianksteen, 1979,

3 The German astronomer Johannes Kepler's notion that the celestial motion of the planets represented a continuous and ever changing song. Through the use of then pioneering synthesis techniques at Bell Labs, Kepler's hypothetical 'music of the spheres' was realised and made audible for the first time.

para. 22).

Taken together I would argue 'being true to the data' and 'being true to the subject' are illustrative of a trend in artists striving to achieve the artistic coherence in a work described in my research aims (section 1.6). It is partly in this 'being true to the data' and achievement of coherence that Gresham-Lancaster's (2012) and Johnstone's (2013) challenge (quoted above) of integrating artistic expression with sonification is addressed. Gresham-Lancaster and Sinclair (2012) write that the job of the designer (or artist) is one of making “what she or he considers as a “just” connection between sound, situation and intention.” (p.70). They go on to say “This means that even if one *can* map anything to anything else, it doesn’t mean one would want to...There is a difference between something that symbolizes something and some-thing that is sympathetic (in sympathy) or naturally resonant.” (pp. 70-71)

2.1.6 Artistic Themes II: Making the inaudible audible

Another artistic theme that is pervasive is the idea that sonifications can reveal something hidden (a hidden truth? see section 2.1.5) within the data and the idea of making otherwise inaudible processes audible (Harris, 2011). Sonifications represent otherwise intangible natural forces though sound. The idea of inaudible ‘music’ being made by natural forces can perhaps be traced as far back as Kepler, who wrote in 1619 “The heavenly motions... are nothing but a continuous song for several voices, perceived not by the ear but by the intellect, a figured music which sets landmarks in the immeasurable flow of time” (cited in Ruff and Rogers, 1979). Kepler had assumed it impossible for the human ear to perceive this music but in an early example of a sonification seeking to make the inaudible audible a realisation of Kepler's celestial harmony “for the ear as well as the intellect” (Bianksteen, 1979, para. 9) was made possible through the “arrival of the computer age” (Ruff and Rogers, 1979). They comment, “we have *made real* what was before only calculations on paper.” [emphasis added] (Bianksteen, 1979, para. 9).

John Luther Adams addresses the matter head-on, writing that one of the artistic ideas behind *The Place Where You Go to Listen* (2009) is to render the inaudible processes of nature as sound:

> Just as microphones allow us to hear sounds that aren’t readily accessible to the naked ear, we can use computers to transform inaudible forces of nature into audible sound… The computer is the primary instrument with which The Place Where You Go to Listen is created. This new instrument allows me to hear and to give voice to visible, tactile, invisible and inaudible vibrations of earth and sky. (Adams, 2009, p.5)

For Adams the key is ‘giving voice’ to natural phenomena: in some cases, creating an aural analogue to an already visible process (mapping changes in sound to the position of the sun in the sky, for example), while in other cases, he makes invisible, inaudible, processes audible (e.g. mapping sound events to changing seismic activity).

Andrea Polli, writing about her work around climate change data, expresses similar ideas, citing the use of sonification as important to constructing a narrative for her work.

> In this project, time and space are compressed in an attempt to allow listeners to hear the patterns of natural systems,

> perhaps comparing these sounds to the sounds of the natural world. The work uses sonification as a way to construct a kind of narrative, emphasizing a climate phenomenon (Polli, 2006, p.45).

She reiterates these themes in a later article:

> Audification brings inaudible sounds to the foreground and changes a listener's experience and understanding of a place. Geosonifications, similarly, have the potential to engage listeners with information about an environment that cannot be audified, yet still has significance like climate or weather data. (Polli, 2012, p.267)

In gathering audience responses to his work Flood Tide, John Eacott received this response from an audience member who refers to learning of inner understandings of natural forces and the work drawing attention to otherwise unheard events:

> It wasn't about learning about the river from the data, it is more about the meditative, inner understanding of natural forces and cycles. And it draws attention to an event that is happening every day in our city and in our lives. (Eacott,2012b, p.193)

This chimes with John Luther-Adams' artistic aims quoted above.

Moving away from data explicitly drawn from the natural world, Polansky (2002) comments on the use of mathematical data, remarking on their profound and universal meanings and summing up, perhaps, why sonification continues to drive artistic projects:

> We're trying to use a set of natural processes, with profound and universal meanings, to instantiate a new musical form. We don't want to hear the Gaussian distribution so much as we want to use the Gaussian distribution to allow us to hear a new music. (Polansky, 2002, para. 10)

2.1.7 Concluding remarks on defining sonification

In grappling with competing definitions of sonification I hope to have addressed the practical point of operationalising my terminology (as stated in section 2.1). Whilst I choose a broad definition of sonification as one where data is translated into sound I reserve the caveat that this must be non-musical data in the first place (see discussion in section 2.1.1). This definition therefore, can be placed into my thesis title, so Sonification as a Means to Generative Music becomes *the translation of non-musical data into sound* as a means to Generative Music. The second half of the title (generative music) will be dealt with in due course.

Through discussing the lively debate over whether sonification can be used for artistic purposes and whether artistic works using sonification as defined above are worthy of the name, I come down in favour of a broad definition of sonification that includes both scientific and artistic sonifications. To reiterate the point made in section 2.1.4 it is far more useful to see sonification as a verb, a process, and evaluate the works on their aims (scientific, or artistic), rather than trying to police a boundary between sonification and data-driven art.

With this definition settled upon, at least in the context of this thesis, concerns move toward the artistic aims of any one work

2.2 Defining Generative Music

Sonification and algorithmic music are inextricably linked (Van Raansbeeck, 2018) and particularly when working with parameter mapping it is inevitable that we are working in the domain of algorithmic composition. Schoon and Dumbois (2009) commented:

> Throughout the history of music, reproducing data by means of sound has played a role, without however being explicitly referred to as "sonification". In retrospect, many compositions that at the time of their inception were classified in categories such as "transformation", "analogy", "numerical games" or "algorithmic composition" can be identified as "data music" (para. 3)

In its simplest and broadest definition algorithmic is music composed with some kind of set of rules (Essl, 2007) or "unambiguous instructions" (Miranda, 2009, p. 129) which have formalized some of the compositional process (Roads, 1996 p. 821, Neirhaus 2009, p. 1). In a parameter mapping sonification this would manifest in a rule such as higher wind speed being mapped to faster musical tempo; behind the scenes an algorithm is at work converting between mph and bpm.

It can be argued that algorithmic music exists in a broader category of generative art, that is "any art practice where the artist uses a system...which is set into motion with some degree of autonomy contributing to or resulting in a completed work of art" (Galanter (2003), cited in Dorin et al 2012, p.239). Why not then "sonification as a means to algorithmic music?" - In chapter 1 I described my desire to explore *generative music.* The following section looks at the definition of generative music as a form or subset of algorithmic music which is defined by its real-time and potentially endless nature.

2.2.1 Generative Music, algorithmic music.

In his 1996 lecture setting out his coinage of generative music, Brian Eno works by example, citing early influences in American minimalism (Terry Riley's *In C* (1964) and Steve Reich's *It's Gonna Rain* (1965) and his own *Music for Airports* (1978) as generative works before finally discussing compositions made with the generative music system KOAN (at that date his latest generative experiment, since superseded by works such as *Bloom* (2008), *Scape* (2012) and *Reflection* (2017)). For him, the defining aspect of generative music is that it "creates itself" (in accord with Galanter (2003) above). He states "Generative music…specifies a set of rules and then lets them [the rules] make the thing." (Eno, 1996b, para.13). He recapitulates this thought some two decades later: "Pieces like this have another name: they're GENERATIVE. By that I mean they make themselves " (Eno, 2017, para. 4).

Others, taking a more academic overview, have tried to classify works and examine the territory claimed by the term generative more rigorously. Wooller et al (2005) identified four strands of music that have been labelled as generative, although they observe that the term itself is "used with different meanings by various scholars and famous practitioners" (para. 2). In their categorisation, Eno's observations about generative work actually fall into one sub-category, "Creative/Procedural", which is characterised by music resulting from processes set in motion by the composer (Wooller et al, 2005, section 1, para. 3) and it is this sub-category that I am most interested in here. In relation to sonification, there is however, an element of their category of “Interactive/Behavioural” where music is generated by a system component that has no discernible musical inputs. I leave to one side their other categories of “Biological/Emergent”- pieces based on evolutionary ideas (such as cellular automata) and “Linguistic/Structural”, where musical schemes are influenced by theories of generative grammar.

Wooller et al (2005) seek to delineate three specific categories of algorithm and place them along a continuum to “assist the composer in designing or selecting algorithms that meet creative needs” (section 5 para 3) and allow musicians and researchers to “differentiate between processes and more clearly articulate the features of computer music systems” (section 5 para 3). Only one of these categories is generative according to their definition: generative algorithms distinguish themselves by displaying a tendency to produce a greater volume of output compared with their input and a greater amount of musical ‘data’ as a result of their process than is implicit before the process is initiated (they cite an example of a chaos music algorithm creating a sequence of notes from one random seed number). This final aspect – producing a greater output than their input is in accord with Eno’s (1996b) thinking. Remarking on Reich’s It’s Gonna Rain he notes:

> The piece is very, very interesting because it's tremendously simple. It's a piece of music that anybody could have made. But the results, sonically, are very complex… you are getting a huge amount of material and experience from a very, very simple starting point.” (Eno, 1996b, para. 8)

However, whilst the examples of generative music put forward by Eno (1996) are processes capable of producing a bewildering number of variations, they are firmly in the transformational category proposed by Wooller et al. (2005), where input and output are relatively matched. These pieces fall short of being generative in Wooller et al's scheme as the existing material is simply re-ordered by the algorithm (or process). In Wooller et al’s words “the general musical predisposition of the transformed phrase is unaltered.” (para. 36). Although the production of a large (possibly infinite) amount of material is important in the characterisation of generative music, I want to draw out a different aspect not covered by Wooller et al, that is the real-time nature of generative music. For me it is this aspect which proves that whilst all generative works inevitably involve algorithms, not all algorithmic music is generative.

2.2.2 Working in real time

Although Collins (2008) has argued “It must be admitted then that generative music as discussed in recent academic literature...often refer to computer-generated algorithmic music which happens to be real-time in production” (p. 239) and Collins and Brown (2009) argue that new terminology is not required: “Generative music itself is to some just a fashionable relabelling of real-time algorithmic composition” (p. 1). Others (particularly Eno) have persisted with the label to describe works whose key feature is their unfolding in real-time. In a 1996 interview with Eno, Williams (1996) writes, “the deeper significance of generative music lies in the fact that it is supposed to exist only in real time, disappearing as it passes" (para 19). John Eacott (2007) summarises generative music as "a system, usually but not exclusively computer based, which has the ability to generate *new output in real-time*, that is to say the sonic output may be heard while the creative processes that generate the output are running [emphasis added] (p. 10). In Eacott's words we hear the echo of Steve Reich's seminal essay *Music as a Gradual Process* "I do not mean the process of composition, but rather pieces of music that are, literally, processes...What I'm interested in is a compositional process and a sounding music that are one and the same thing" (Reich, 1968, p. 34). But are all process pieces generative?

If algorithmic composition is defined as broadly as to take in all work that uses formal rules or semi-automatic processes (Essl, 2007), then all music generated by following a rule structure comes into its purview. It takes in works specified by systems of rules in classical composition such as species counterpoint or serialism (Cope, 2009, Spiegel, 2009, Essl, 2007) as well as contemporary examples of computer driven algorithmic music in the work of Hillier (*Illiac Suite*, 1957) or Xenakis. Generative music can be contrasted with those methods and composers who used processes or algorithms to create their music materials and then use the outputs of their algorithmic calculations to produce works that are then fixed in a score or other medium[4]. Roads (2001), Doornbusch (2005), Essl (2007) and Carl (2009) all refer to Xenakis (and others) using algorithms "out of time" for creating musical scores or developing material for a composition that "once realized in the notated form...were fixed" (Carl, 2009, p5). Gresham-Lancaster (2002) comments specifically on Xenakis' method:

> In informal conversations, he repeatedly stated his conception for using these various formulas and processes as a compositional tool. To paraphrase, he said, "The mathematics generate the raw material, a generated virtual stone and the composer needs to actively sculpt that into musical existence." (Gresham-Lancaster, 2012, p. 208)

Eno has likened generative music to gardening, in contrast with other non-generative music which is more akin to architecture.

> I always say the difference between classical and contemporary music is the difference between architecture and gardening. With architecture you know in advance what you're going to get, you specify it all, it's all written down and drawn out and it is brought into existence. With gardening it's not really like that. What you have to do is put together some elements that you are kind of familiar with and watch what happens to them and how this garden turns out compared to that garden is dependent on a whole lot of factors (Eno quoted in Wray, 2016, para. 7)

> "...evolution theory says that complexity arises out of simplicity. That's a bottom up picture. I like that idea as a compositional idea, that you can set in place certain conditions and let them grow. It makes composing more like gardening than architecture" (Eno quoted in Tingen, 2005)

Algorithmic processes can exist either side of this gardening/architecture dichotomy. Appropriately, given Xenakis other life as an architect, his use of algorithmic processes to build components for final fixed compositions is characteristic of the architecture analogy used by Eno.

Consider an early example often cited (Duckworth, 2005, p.1 , Roads, 2006, p. 823, Harley 2009, p. 110, Boden and Edmonds, 2010, p. 30 and Barrass and Vickers, 2011) as a pre-computer example of algorithmic composition with an 'extra musical' source : the Musikalisches Würfelspiel, musical 'dice

4 Although I cite him as an example, this is perhaps a little unfair and partial characterisation of Xenakis' complete output. Whilst it's true that his early stochastic works used the computer to automate and speed up his statistical calculations from which orchestral scores were drawn up, he did recognise that a unification of the calculation and sound production process was a desirable and inevitable step toward 'total composition' (see Serra, 1993)

games’ attributed to Mozart (although with some debate and uncertainty [Zbikowski, 2002]). Even though decision making is given over to an external agent (the rolling of dice) the musical material is assembled to create a fixed-duration waltz, albeit one that is one of 45,949,729,863,572,161 potential versions (Zbikowski, 2002, p. 148). The dice are not rolled in real time but ahead (or out) of time.

Now consider another example, cited by Eno (1996) and labelled by him as generative: Terry Riley’s *In C* (1964). The ‘rules’ or generative algorithm is contained in Riley’s performing directions included with the score:

> All performers play from the same page of 53 melodic patterns played in sequence...Patterns are to be played consecutively with each performer having the freedom to determine how many times he or she will repeat each pattern before moving on to the next” (Riley, 1964, para. 1-2)

The performers make real-time decisions about whether to repeat, or move to the next measure. An ensemble’s progression though the piece cannot be determined in advance; decisions are taken (within the rules of the piece) in real time, generating variety and unpredictability at each step as the piece is playing[5]. Running with Eno's gardening/architecture analogy, Riley has specified the 'seeds' or 'plants' in the garden of *In C* but the individual conditions of each performance dictate its final form.

2.2.3 Infinite Music? Music as a gradual (and endless) process

There does seem a contradiction in Eno's 1996 argument when he describes his work *Music for Airports* (1978) as generative as well as Reich's *It's Gonna Rain* and Riley's *In C.* All of these pieces run for set durations. With the exception of *In C* which can vary from performance to performance, both *Music for Airports* and *It's Gonna Rain* are fixed. Despite the processes used to make the pieces being generative in of themselves, a single running of these systems was recorded and released as the final product and due to the limitations of the final medium of presentation the process ceases to unfold in real time. In 2017 Eno explained this compromise:

> I wanted also that this music would unfold differently all the time…But recordings - whether vinyl, cassette or CD - are limited in length, and replay identically each time you listen to them. So in the past I was limited to making the systems which make the music, but then recording 30 minutes or an hour and releasing that. (Eno, 2017)

On similar lines Essl (2007) notes “As this music has no beginning or end, the distribution on a reproductive medium such as compact disc seems highly inappropriate” (p. 122). The ideal condition for generative music is its second defining characteristic: its infinite scope – where beginning and end are dispensed with and the real-time evolution of the piece can go on (theoretically) forever. Discussing the evolution of generative

5 Tero Parviainen analyses Terry Riley’s In C from this perspective in this blog http://teropa.info/blog/2017/01/23/terry-rileys-in-c.html, with some fascinating visualisations of the possibility space being traversed. Parviainen observes “If we set our average branching factor to, say, 4 (assuming 1-8 choices at each point) and the number of decision points to 265 (conservatively assuming a player would repeat each pattern 5 times on average), our game tree complexity would be 4265 = 35 * 10158. That's 35 followed by 158 zeros. A very large number. Suffice it to say no one will ever hear all the combinations made possible by the "In C" performing directions, even if everyone in the world did nothing but play the piece in trios until the heat death of the universe.”

music out of early ambient[6] works *Discreet Music* (1975) and *Music for Airports* (1978), Toop (2004) summarises Eno's intentions for generative music as "The desire to make a music that exists in a state of being, theoretically without beginning or end" (p 190). Looking back on the evolution of his generative ideas, Eno himself comments, on the release of *Reflection* (2017) as an app (as well as a CD) as the ideal realisation of his generative ideas " the app by which REFLECTION is produced is not restricted: it creates an endless and endlessly changing version of the piece of music." (Eno, 2017, para. 7).

Essl (2007) differentiates generative music by its wish to free itself from the temporal limitation; to be more like "the rustling of leaves in the wind...as an (infinite) stream of sound" (p. 121). This has the ring of John Cage's exhortation that art (and his music) should imitate nature in the manner of its operation (Cage, 1963, p. 31). Commenting on *Reflection (*2017), Eno has also reached for an analogy from the natural world speaking of a "constantly morphing stream (or river) of music." (Eno, 2017, para.8). Elaborating on this river theme he states:

> My original intention with Ambient music was to make endless music, music that would be there as long as you wanted it to be. I wanted also that this music would unfold differently all the time - 'like sitting by a river': it's always the same river, but it's always changing….. But the app by which REFLECTION is produced is not restricted: it creates an endless and endlessly changing version of the piece of music. [capitals in original] (Eno 2017, para. 7)

This formulation of the endlessly changing river is essentially a rewording of the aphorism "no man steps in the same river twice", generally credited to the Ancient Greek philosopher Heraclitus[7]. As an analogy it neatly captures the idea of the generative work as a recognisable entity (the river) that is nevertheless constantly changing.

I wish to avoid any misconception in this thesis that the infinite scope of generative music is synonymous with music of extreme duration, assuming the raison d'être of a generative piece is to last for all time. This aspect of infinite (and by implication generative) music is satirised by Collins (2002) imagining a maestro drawing the audience's attention to a particularly good passage thousands of years hence "Watch out for a particular mark of my genius in 43920 AD." (para. 1). However, having constructed a generative algorithm, the natural realisation of the music created from this algorithm is one that is constant, endless and endlessly changing. In relation to algorithmic music Collins (2009) observes:

> Algorithmic music enables extended forms; in the extreme…larger expanses of time are often invoked by installation works running over extended periods, or by programs constantly streaming algorithmic music over the Internet. Whilst the audience may drop in and out, works such as Jem Finer's Longplayer or Leif Inge's 9 Beet Stretch stream on (Collins, 2009, p.107)

The notion of the audience dropping in and out whilst the music streams on points to the definition of infinite

6 Eno tends to use the terms generative and ambient interchangeably, although he acknowledges that his original conception of 'ambient' is somewhat corrupted. He comments in relation to the tape loop system used in Music for Airports "I made many, many pieces of music using more complex variations….In fact all the stuff I released called ambient music (laughter), not the stuff those other 2 ½ million people released called ambient music -- all of my ambient music I should say, really was based on that kind of principle" (Eno, 1996b, para 13.) and two decades later "Anyway, it's the music that I later called 'Ambient'. I don't think I understand what that term stands for any more - it seems to have swollen to accommodate some quite unexpected bedfellows - but I still use it to distinguish it from pieces of music that have fixed duration and rhythmically connected, locked together elements." (Eno, 2017, para 2)

7 The exact origin and attribution is the subject some debate. In Plato, Cratylus, 402a Socrates says "Heracleitus says, you know, that all things move and nothing remains still, and he likens the universe to the current of a river, saying that you cannot step twice into the same stream" see https://plato.stanford.edu/entries/heraclitus/

I am aiming at: music existing in a condition unbounded by duration. This draws to mind an aphorism of Henry David Thoreau quoted by John Cage “music is continuous; only listening is intermittent” (Cage, 1981, p. 3, Gann, 2010, p. 116).

Roads (2001) provides one of the most thorough settings-out of musical timescales and particularly the notion of an infinite timescale in his drawing out of a hierarchy of musical durations (pp. 3-4). He places the kind of works discussed (and satirised) by Collins into a time scale category of ‘supra’ which “extends into weeks, months, years, decades and beyond…”. He places a further category of 'infinite' beyond this as a “mathematical ideal” which is not as removed from music as it seems, being written for example, into the Fourier analysis of infinite sinewaves (Roads, 2002, p. 8). Capturing a similar idea, Kramer (1988) describes pieces conceived in vertical time. Such pieces do not begin but merely start, they do not end but merely cease (p. 55). He quotes Stockhausen, who is more expansive and expressing similar ideas, on his 'moment form':

> Musical forms have been composed in recent years which are remote from the scheme of the finalistic dramatic forms. These forms do not aim toward a climax, do not prepare the listener to expect a climax, and their structures do not contain the usual stages found in the development curve of the whole duration of a normal composition: the introductory, rising, transitional, and fading stages. On the contrary, these new forms are immediately intensive, and the main point which is made at once remains present at an equal level to the very conclusion. They do not induce constant waiting for a minimum or a maximum, and the direction of their development cannot be predicted with certainty. *They are forms in a state of always having already commenced, which could go on as they are for an eternity*” [emphasis added] (Stockhausen quoted in Kramer, 1988, p. 201)

However, as Eigenfeldt (2016) points out, this conception of moment form (and Stockhausen's pieces based on it) relies upon discontinuity between many moments whereas “ambient music most often contains only a single moment” (section 3.2). Along similar lines John Luther Adams cites James Tenney's concept of 'ergodic form' as an influence. In ergodic form, pieces of music “conceived, composed and experienced as one single, complex, evolving sonority...” and “any moment of the music is statistically equivalent to any other moment” (Adams cited in Carl, 2012, p.211).

Collins (2002) is probably correct to puncture with satire the idea of infinite compositions from the point of view that the longer the piece, the greater the genius of the composer and the greater the demand on the audience to endure long listening durations to fully appreciate this genius. However, anyone working with generative systems that are intrinsically open ended seems to have little choice other than to accept an idealised infinite – or unspecified – duration. This is the nature of generative music and one of its defining characteristics. That is not without the compromise (see Eno, 2017 quoted above) of limiting their work to an arbitrary run (the length of a CD, concert, the lifetime of a web-server) but such fixed-length realisations only ever represent a slice of a *theoretical* (“the mathematical ideal”, in Roads' terms) infinite continuum.

2.2.4 Concluding remarks on defining generative music

Brian Eno is fond of his analogy of generative music being like gardening rather than architecture. This gardening analogy has also been simultaneously arrived at by Dorin (2001) who argues that some generative art is experienced like a garden:

> Some interactive computer software operates more like a garden... The experience of a garden is very different to that of a film. The 'audience' might walk through the space or sit awhile. The birds might flutter, the leaves drift and the water flows. A person might disturb the quiet by shouting, they might interact with the flow of water by stepping in the stream. Or they might not. Whatever the audience decides to do, by their presence or their absence the garden will change. If the audience departed to return later, the sequence of events they experienced will not be repeated as if it were a stage play or film. There is no script, the garden flows constantly according to the natural law which audiences are also helpless to obey. A garden, therefore, is not usually considered to reach a state of 'completion'. Though its passage through time may be marked by seasonal/cyclic changes and other convenient measures, the garden is intrinsically dynamic, always in a state of becoming (p. 50)

In this single quote the two elements from my argument above are brought together. The generative work (aspiring to the state of a garden) is continuously flowing (the real-time element of generative work described above) with sequences of events not repeated if the audience departs to return later, in a dynamic and constant state of becoming (what I have termed the infinite nature of such works).

As promised in section 2.1.7, this definition of generative music, as a species of algorithmic music that evolves in real time with infinite scope can now be put into the title of this thesis to complete its expansion: *the translation of non-musical data into sound* as a means to *music that evolves in real time with infinite scope.*

2.3 Sonification as a means to generative music: some touchstones

Sonifying data would appear to be an ideal algorithmic strategy for the creation of generative work. However, the data itself has to be changing in real time and be infinite in scope[8]. Sonification has generally been employed with discrete fixed datasets being used to create works that are then fixed in their duration and realisation – for example, Quinn's *Seismic Sonata* (2005) which takes data from one earthquake event and translates it into a c. 7 minute sonata form. Sturm's (2003) *Pacific Pulse,* an eight channel work using data from ocean buoys in November and December 2001, Sturm comments “A total of 266 minutes of sound was synthesized, of which about 40 minutes was used in the piece.” (Sturm, 2005). Tom Duckich's *Can you hear me now? Sonified Weather: Spokane & Seattle* (2004) takes five years' worth of weather data to produce five pieces of music released on CD.

The three exemplary works presented in this section demonstrate the use of real-time data to create generative works (although only in one case explicitly labelled as such) that satisfy my criteria above. These works have not only served as touchstones in my own exploration of the territory of sonification as a means to generative music, but also serve as examples of other artists decision making and their struggle for artistic coherence between the data sonified and the sounds heard.

8 With the caveat that this is in accordance with my argument on the definition of infinite – examples might be data on weather, astronomical data, financial markets or transportation networks which will continue to be produced with no set or intrinsic end point (in strict terms they are only as infinite as there are still people, or computers around to produce them see Collins 2002). A counter example may be a statistical sample with a discrete number of records – opinion poll data, or a census for instance.

2.3.1 John Luther Adams' *The Place Where You Go to Listen*

John Luther Adams' installation work *The Place Where You Go to Listen* (2006-) (henceforth in this section, *The Place...*) has been playing continuously for more than a decade at the Fairbanks Museum of the North at the University of Alaska. Adams sets out the scheme for the work and its genesis in considerable detail in his book The Place Where You Go to Listen: In Search of an Ecology of Music (Adams, 2009). Without going into great detail on its inner workings here it is worthwhile engaging in a précis of its nature.

The Place... is a sound and light environment designed by Adams to sonify several streams of environmental data. Musically, his method is a kind of subtractive synthesis, taking white noise and applying filters to create tuned tones.

Elements of the installation include:

- a 'day choir' and 'night choir': continuously sounding drones based on filtered noise, which respond to the time of day and whose bandwidth (spread of tones in the harmonic series) is governed by the reported visibility from meteorological data. Adams has engineered this so a cloudless day with clear weather produces a wide range of tones (over four octaves) whereas a cloudy day produces a narrower range (just two octaves) (Adams, 2009, p. 121). The day and night choirs move around the installation space according to the position of the sun.
- The moon: a narrow band of noise (Adams, 2009, p. 124), the bandwidth of which is determined by the phase of the moon (wide at a full moon and zero, briefly, at a new moon). Like the day and night choirs, the position of the moon in the sky affects its spatial position within the multi-speaker installation environment.
- 'Aurora Bells': high frequency components driven by readings of the magnetosphere from several stations in Alaska, sonifying the Aurora Borealis above Fairbanks. The greater the fluctuation in the magnetosphere the greater the amplitude, and the narrower the bandwidth (Adams, 2009, p.132).
- 'Earth Drums': low-frequency drum-like sounds generated from data from several seismic stations in the Alaska region (Adams, 2009,p.132).

In summary, *The Place...* is a large-scale parameter mapping sonification taking a range of live environmental data and transforming it into a musical result; an “analogue of the events occurring across the Alaskan landscape” (Rutherford-Johnson, 2017, p. 230). Adams comments on the importance of the real-time realisation of the piece and the desire to reflect the rhythms of nature, rather than compressing or otherwise altering time[9].

> Events unfold in the same tempos as nature...shaped by the arcs and rhythms of day and night...the rate of change is usually too slow to be perceived. Yet over the course of hours, days and months, the changes are increasingly dramatic. From day to night, from winter to summer (Adams, 2009, p. 6)

9 This contrasts with (for example) the approach of Duckich (2004) mentioned above.

These thoughts are echoed by the critic Kyle Gann, describing the changes in *The Place...* “The Place changes radically from night to day, from winter to summer, from season to season.” (Gann, 2006, para. 3). Adams comments further on real time: “Real time is an essential element in the composition and experience of The Place Where You Go to Listen. This is not a predetermined sequence e of musical events....It is a dynamic system of visible and audible forces interacting in a constantly changing environment (Adams, 2009, p. 7). Alex Ross describes the installation thus:

> “[The Place...] is a kind of infinite musical work that is controlled by natural events occurring in real time...the place translates raw data into music: information from seismological, meteorological, and geomagnetic stations in various parts of Alaska is fed into a computer and transformed into a luminous field of electronic sound” (Ross, 2010, p. 176)

Ross, a music critic, shows no reservations about describing the piece in musical terms (perhaps illustrative of Vickers and Hogg's (2006) contention: if someone has a musical experience with sonified data, then its music) and in the first sentence quoted he also neatly captures my definition of generative music.

Adams' piece is not only exemplary in terms of its demonstration of a real-time generative work based on data sonification. His relentless self-analysis and focus on being 'true to the data' (see section 2.1.5), written about in the book accompanying the piece (Adams, 2009) demonstrates the striving for artistic coherence between data and sounds heard that I set out in my research objectives (section 1.6). In an interview with Alex Ross, Adams comments “I knew that it had to be real - that I couldn't fake this, that nothing could be recorded. It had to have the ring of truth” (Ross, 2010, p. 178). Adams' description of the process of arriving at a mapping scheme that is artistically satisfying serves as a template for my own analysis of my portfolio in the following section.

Other authors, on summing up Adams' work, have commented on the strong coherences between changing data and sound. Herzogenrath (2009) contrasts Adams' work with earlier attempts to represent natural phenomena in music, writing “Adams does not only imitate nature in its manner of operation, as Cage still does; he taps into nature's dynamic processes themselves for the generation of sound and light” (p. 226) and furthermore describes the result as a sort of ecosystem:

> Adams solves this problem [the problem of representation] by leaving the executing/processing energy to the processual forces of nature itself. Music and environment thus become an ecosystem of a dynamics of acoustic and optic resonances interacting in/with an environment in constant flux (Herzogenrath, 2009, p. 228)

In a personal reflection, Ross (2010) describes his experience of *The Place...* demonstrating neatly the strong coherence between data, sound and what the data represents:

> The first day I was there, The Place was subdued...Clouds covered the sky so the Day Choir was muted. After a few minutes, there was a noticeable change: the solar harmonies acquired extra radiance, with upper intervals oscillating in an almost melodic fashion. Certain that the sun had come out, I left The Place, and looked out the windows of the lobby. The Alaska Range was glistening on the far side of the Tanana Valley (p. 177)

This passage perfectly sums up what Gresham-Lancaster (2012) referred to as tangible congruence which is used to build one element of what I have termed artistic coherence[10]. In Adams' words “data and music resonate together” (Adams, 2009, p.27): a change in data clearly produces a coherent change in the sounds heard. The brighter sonority of the Day Choir led Ross to be certain that the clouds had lifted outside and the

10 In a similar vein Rutherford-Johnson (2017) describes Adams' scheme as mediating nature and ecology to achieve 'stylistic coherency' (p. 230).

sun was out (contrast with the lack of coherency if brighter weather involved a dulling of the sonority[11]).

2.3.2 John Eacott – Flood Tide

Eacott (2011) introduces *Flood Tide* thus: “Flood Tide is a musical performance generated in real time from live tidal stream data translated into musical notation and read from computer screens by an ensemble of orchestral instruments” (Eacott, 2011, p. 189). *Flood Tide* satisfies my real-time condition set out in section 2.2.2 with the data and resultant music unfolding together. In a separate write up, Eacott (2009) himself describes the work as generative, elaborating “Flood Tide generates music from the flow of the Thames, using a physical impeller in the river connected to a SuperCollider patch that interprets the gradually changing speed of flow to produce live notation for instrumentalists.” (p.118).

This live notation and use of live musicians produces a series of discrete, timed performances where Eacott strives to use live data from that specific time and from a specific place, although there have been performances using pre-calculated data (Eacott, 2013) and though there is also a version (since 2014) operating as a continuous installation, a mechanical sculpture at Trinity Buoy Wharf (“Floodtide: Listening Post”, 2014). Flood Tide is illustrative of the problems discussed in section 2.2.3: each performance of *Flood Tide,* at a different location (contrast with the fixed location of John Luther Adams' *The Place...*), at a different time, can be reconciled as dipping into an infinite, unrepeatable continuum of flood data (indeed, on Eacott's website notation is generated continuously from a fixed tide sensor). Evoking Cage’s observation from Thoreau (see section 2.2.3) we could say that streams of data are continuous but the sonifications of them are intermittent.

Eacott (2012a) displays the same concerns as John Luther Adams (section 2.3.1) in that the data is represented fairly whilst still arriving at a musical result – the ‘being true to the data’ tendency. He comments, “Rather than merely aiming for scale or complexity, it is more interesting for me to strive to generate coherent and elegant forms that represent the incoming data accurately and clearly while generating musical structures that engage an audience.” (p.287).

In further engagement with the themes discussed in section 2.1, he also recognises that there are trade-offs between the scientific display of tidal data that may be possible though sonification and his desire to create a musical performance “If my intention was to represent the changes in tidal flow as clearly as possible, I would not choose to use 40 musicians. My aim is to make a musical performance, which is generated by tidal flow…” (p.287). However, he sees value in the enterprise, citing the artistic themes discussed in section 2.1.6 “...the work acts as a kind of intervention with nature and a shift in perspective. *To make sonic what is normally without sound*.” (p.287).

11 I concede here that the idea of 'brighter' and 'duller' sonorities is subjective and potentially culturally defined. On this point Gresham-Lancaster talks of “culturally bound decisions” (Gresham-Lancaster, 2012, p. 210) - see discussion in section 2.1.3. Walker and Lane (2001) neatly demonstrate the problem of 'obvious polarities' in sonification schemes demonstrating that in response to a sonification of amounts of money, visually impaired users associated *lower* sounds with more money (imagining a large amount of money would make a low pitched thud, where as a single coin would make a high pitched clink). This was the exact opposite of the intended sonification design.

2.3.3 Robert Watts, David Behrman & Bob Diamond - Cloud Music

There is precious little written information about *Cloud Music* (1974-79), an installation piece conceived by Robert Watts and realised with the help of David Behrman (sound) and Bob Diamond (video engineering). The work itself predates the coinage of both sonification and generative, so is never referred to in those terms by its authors, although it fits neatly into my definitions of those terms.

Cloud Music consists of a primitive synthetic drone driven by a video analyser translating brightness from a video signal aimed at the open sky. Movements in the clouds alter the brightness signals (the data being sonified). Behrman (in Watts et al, 1992) elaborates on the sound scheme:

> Sound is produced by eight banks of audiorange function generators, four to a bank, each of which is tuned to a pre-selected four-part “chord” made up of pure modal or microtonal intervals. Six of the banks can each be detuned to four parallel transpositions by an output from the video analyzer. Any harmonic change corresponds to a minute change in light of a crosshair in the video image (Watts et al, 1992, p. 153)

Cloud Music, with its focus on nature and gradually unfolding structure, has much in common with both John Luther Adams’ The Place… and John Eacott’s Flood Tide. It attempts to sonify Watts’ “poetic idea of listening to the clouds” (Randerson, 2013, para. 9). In an interview with Randerson (2013) Behrman explicitly links Cloud Music to chance aesthetics and John Cage

> “If you think of a conventional composition as an object that is fixed from beginning to end, [instead] we were creating a situation to be explored by musicians…the clouds could randomly trigger things… Cage used chance, [sic] he used the I-Ching to open up a situation. And, in a way, the clouds moving across the sky is like the I-Ching. “ (Quoted in Randerson, 2013, para. 16)

Typifying the infinite nature of generative works, in this quote Berhman neatly contrasts a generative work such as *Cloud Music* with the fixed nature of conventional composition. The use of a live video feed, clearly positions the work as one which unfolds in real time. Indeed, the Smithsonian (current custodians of the work) comments “*Cloud Music* enables us to "listen" to video as a nature-driven event unfolding in real time”. (Smithsonian, n.d.).

Talking of his artistic motivations Watts says, “Since 1965 clouds, sounds, indeed the whole phenomenology of the natural environment has pervaded most aspects of my work” (Watts et al 1992, p. 152). In creating the sound element to the piece, Behrman argues that the chosen sounds aim to reflect the subject matter, creating an “interweaving of slowly shifting, multilayered harmony that parallels the movement of the clouds” (Watts et al 1992, p. 152). In an interview with Randerson (2013) Diamond comments “the whole idea of it was to almost be able to feel the shape of the clouds” (quoted in Randerson, 2013, para. 9). Watts' and Diamond's words recall Gresham-Lancaster and Sinclair's (2012) comments on natural resonance in a sonification scheme and in this brief discussion of his artistic motivations is the germ of the kind of artistic coherence that is the subject of this thesis. Like Adams' *The Place...* and Eacott's *Flood Tide* the rhythms of *Cloud Music* are in keeping with their source material in nature, either gradually drifting with clouds across the sky, or becoming very active in times of high winds (like sailing, in Watt's words). Time is not compressed or altered. On a cloudless day, presented with nothing but blue sky, the harmony remains fixed, with no attempt to force the installation into action.

2.3.4 Concluding remarks on touchstones and defining artistic coherence

The definition of a touchstone is a standard by which something is judged or recognised. I chose to write about these three pieces because all three are exemplary of the approach worked up throughout section 2, where there is a synthesis of sonification of a live, constantly changing data flow into a live, constantly changing piece of music. John Luther Adams' documentation of his process, making explicit his mapping procedures and the artistic motivations behind them and by these means showing that they are anything but arbitrary, serves as a model for my own analysis in the subsequent sections.

All three pieces show strongly the kind of commitment to artistic coherence that I am aiming to investigate in my own works and as stated in section 1.6 the exploration of the artistic coherency of the realisation of these works is a key research question. Having reviewed other perspectives in the literature and specific works it is pertinent at this point to offer a further terminological definition of 'artistic coherence' and the yardstick by which I will be subsequently evaluating my own works. Artistic coherency, as I see it, is made up of two elements.

Firstly, the relationship between the underlying data and the structure of a piece. Artistic coherency is built where the sonification scheme reflects and articulates the underlying data - the 'tangible congruence' that Gresham-Lancaster (2012) identifies (see section 2.1.4) - where changes in the data relate to changes to the sounds heard. There has often been an emphasis on being 'true' to the data (see section 2.1.5) and a desire to reveal something 'hidden' in the data (see section 2.1.6); part of creating a coherent work is to 'honour' the underlying data (otherwise the choice of data or can be seen as arbitrary and interchangeable).

Secondly, the relationship between the soundworld and the underlying data. An artistically coherent work demonstrates strong (coherent) relationships between data and sounds heard. The coherency of artistic choices is perhaps harder to judge as the sounds employed in a piece are the choice of the individual composer however, some generalisations can be made. For example, for *The Place...* in choosing a sound appropriate to the subsonic earthquake data Adams has chosen low-pitched drum like sounds and in representing the aurora, high pitched bell-like sounds. If these two were reversed an incoherency would be introduced (at the very least we might be entitled to question the logic of these choices). Whilst the synthesiser tones of *Cloud Music* are abstract, Behrman draws a parallel between the slowly shifting harmonies and the movement of clouds. The choice of an aggressive soundworld – clashing percussion or distorted heavy metal guitars – would be at odds with the data and conception of the artwork.

3. Methodology

Although each work in the portfolio has involved its own process of realisation, which is detailed in section 4, there is something of a generalised methodology for the creation of generative works using sonification which has been refined throughout the process of producing the portfolio. A key part of this, given the nature of generative music and its key features detailed in section 2.2 (unfolding in real time on a potentially infinite timescale), is the discovery of data sources that are similarly updated in real time and are (in theory) infinite in scope.

Although there is no general rule – or search engine – for achieving this, the discovery of the OpenSky data on flights, for example, was prompted by a news story (where flight tracking websites, something hitherto unknown to me, were referred to). This in turn lead to the discovery of the the national grid data. I wrote this in my study journal:

> I was praising ‘the geeks’ for making the air traffic data available in a convenient API and thought something similar might exist for trains, then I got to thinking about other big, national systems which might churn out data. Somehow I alighted on 'gridwatch' which published realtime data from the national electricity grid...

Similarly, the data driving *Protest Songs* came from signing a parliamentary petition and noticing the link to the data on the government website. The Shipping Forecast was firmly in my consciousness to begin with, I actively set out to find if it was available as data, rather than radio broadcast. Similarly an interview which mentioned the gigantic and ever growing size of Wikipedia led me to search out if such statistics were available on a near to real time basis.

After initial interest, some data sources are rejected due to not fitting the two criteria above – some update too infrequently to provide enough musical momentum (although 'enough' is something of an elastic concept and the rate of change in data itself becomes a key part of the conception of a piece as will be discussed later). Likewise any data that is historical and fixed has to be rejected on the basis of not being able to satisfy an infinite generative scheme.

If these two criteria are satisfied then the practicalities of working with the data are considered through an initial evaluation of the properties of a dataset (which statisticians sometimes refer to as 'eyeballing' the data) – does it contain a parameter that varies over time, that suggests some kind of pattern? At this stage initially promising data sources may be also be rejected if no 'interesting' data is available or is not easily manipulated. An unfinished piece based on real time lightning strike location data, for example, comes to mind, the data was proprietary and not released in a format amenable to my purposes.

Once it is established that there is 'something to work with', then begins the creation of a piece. The process is an iterative one, involving experimentation (which could be characterised as trial and error) both with the use of the data (whether transposition or scaling is required, for example) and auditioning the sounds that are heard. As detailed in the 'Genesis and Influence' sections for each work in chapter 4, there is often a conceptual starting point for the piece which influences how the data is used and the palette of sounds. This concept is usually linked to the data itself – it's source or content. The soundworld also, usually, to a greater or lesser extent flows from the content of the data (in a way that achieves artistic coherency as outlined above). However, such conceptual beginnings are not rigid and in fact can be quite vague to begin with, leading to different avenues being explored once the creative process is in train.

Over the course of my research, as more pieces were created for the portfolio, it was inevitable that this methodology was refined and developed. Certain successful strategies were repeated and built on and blind alleys discovered early on in the research avoided latter on. As the works are described in chapter 4 I will revisit the methodology periodically, reflecting these discoveries before considering the methodology with reference to the whole portfolio in chapter 5.

4. The Works

In the following section each of the works in the portfolio are examined. Each piece is subject to three sub-sections. 'Genesis and Influence' sets out the inspiration behind each work, the data which drives the sonification and the soundworld it produces. The 'Technical Report' gives details of how the sonification is achieved, in particular how the mapping of data to sound is achieved. Finally, in the 'Evaluation' each pieces' place in the portfolio is considered with reference to the research aims set out in section 1.6, the discussions in chapter 2 and in relation to the methodological statement in chapter 3. Pieces are also discussed with reference to the development of my methodology and other works as I progressed through the portfolio.

The pieces are presented in roughly chronological order of their creation (often one or two pieces would be worked on concurrently). Thus, with each piece different facets of my exploration of sonification, or ways of answering my research questions, are looked at. Often composing one piece and deciding on its mapping scheme raised further questions about how subsequent pieces would be composed and how the data driving each piece would be addressed. This is hopefully reflected in their chronological presentation .

In addition to this chapter, a series of video tutorials are included (see USB contents), which show the individual workings of each piece.

4.1 *Troy Ounce*

Troy Ounce is a sonification of the international gold markets, tracking fluctuations in the price of gold in four currencies.

4.1.1 Genesis and Influence

After completing *Playing the Weather* (see section 1.5) I was casting around for another dataset that was easily available via the internet and updating at a frequency amenable to making an interesting musical scheme and began researching the possibility of using financial data. A bewildering array of data is available for the purposes of studying world financial markets – not just stock prices but volumes traded, high and low averages and various analytical ratios such as earnings per share. I struggled initially to conceive of any scheme that could take in this data and provide me with a conceptual foundation to base the work on (in Landy's (1994) phrase " something to hold on to"). How to respond to this data, and what is the sound of money?

My answer came from what initially may seem an unrelated source. I had read about Janeck Schaefer's *Tri-phonic Turntable* (1997) – a sound art work where a modified turntable with three arms allows Schaefer to play either three records at once or one record in three different places at once as well as at variable speed: “records can be easily accessed in many time frames/ places simultaneously...This invention could multiply, magnify and manipulate the essential physical surface of sound in as many ways as was practically possible” (Schaefer, 2001, p.73). Through this device, Schaefer mines and appropriates the sonic content of the existing LP record to make a live sound art.

This had me thinking about making a similar sounding device in software – accessing different parts of a sample simultaneously, in analogy to Schaefer’s use of the LP record. In software the physical restraints of the turntable are removed; a virtual ‘100-arm’ turntable could be produced if desired. The variation in playing speed could be implemented by playing the sample at a slower rate with the consequent lowering in pitch that is characteristic of this technique. However, with digital technology it is possible to lower the speed of the recording independent of pitch. I achieved this using a repurposing of the phase-vocoder example patch in Pure Data. The other advantage of this effect is that when the speed is zero, the audio can be ‘frozen’, unlike an LP which simply stops.

In another work of Schaefer’s, *Extended Play* (2007), variable-speed turntables (each with their own part – cello, violin, piano) are set into playing by a motion detector as visitors move around the installation. The parts assemble in a random order not unlike Brian Eno's tape loops (see section 1.2).

This random starting and stopping of sound turned out, for me, to be the ideal way of looking at the financial data I was attempting to sonify. It occurred to me that what I wanted to express artistically was not the content of the financial data per se (whether a stock price had gone from 100p a share to 99.5p) but the organic patterns generated by the constantly shifting data.

Visually, when footage of screens in vast trading floors is shown there is a sea of red and green; as the data changes these coloured points change. The patterns, to me, resemble natural ones, as one might see as wind blows on a cornfield. As explained in section 2.1.4 in relation to John Cage’s *Reunion* (1968) what is being sonified is not the absolute values of the market data, but the human activity, the aggregate of thousands, millions of small trading decisions making it up.

Schaefer's use of 'found' material (i.e. an existing recording, a practice sometimes called plunderphonics, or simply sampling) led me to using *Gold!* by Spandau Ballet (1983) as the raw material for the piece, representing a sort of musical pun. Schaefer comments on the use of found sound: “The history of the record has left vast amounts of vinyl lying dormant across the globe; virtually any sound that one might want to use is awaiting rediscovery, accidental encounters and unknown uses” (Schaefer, 2001, p. 73). The recording would be manipulated it as if it were on Schaefer’s Tri-Phonic turntable, with the motion of the turntable going either forward or backward depending on upward or downward shifts in the price of gold. As such shifts are generally small (in the order of fractions of cents or pence) the recording would be reduced to small quanta of sound; raw sonic material.

4.1.2 Technical Report

Troy Ounce is made up of two elements: a Python script which 'scrapes'[1] financial pages for the current price of gold in four different reserve currencies and passes it to a Pure Data patch to produce the sound.

Each currency represents a 'channel' in a Pure Data patch (or arm of the turntable in the analogy to Schaefer's work) which is playing a copy of *Gold!*. Each channel is a phase-vocoder object called 'stretch', its input argument is a 'pointer' – a position in the file (analogous to the position of the needle on a record). This is expressed as a percentage. With each reported change in the gold price, the pointer moves, either forwards in the file, or backwards (wrapping around at 100% and 0% respectively). So a shift in the price of gold from $1010.10 to $1000.05 (the order of magnitude is small) results in the pointer shifting 0.005% though the file – sometimes just a matter of some few samples – over 10 seconds, finishing just in time for the next instruction (prices are polled from the Python script every 10 seconds). In a very active market the effect is a continuously moving pointer, but in reality the sound freezes quite frequently until the price changes.

After some auditioning, to create a more interesting texture, I decided to begin each currency channel at a different place in the sample (roughly in quarters, at points 1%, 25%, 75%, 99%). This has the effect borrowed from Schaefer of playing a record (in this case the audio sample) in several places at once.

Although the prices often move together, exchange rate effects mean that they are not moving in lock step. As they diverge, the piece can move from discord (particularly when Tony Hadley's rather strident vocals are frozen in time) to more 'ambient' moments. Drums sounds, for example, render as noisy bursts when stretched. If left running, the piece would carry on producing infinite variations upon Spandau Ballet's original material.

4.1.3 Evaluation

Troy Ounce distinguishes itself as a sonification of human activity rather than of natural phenomena (compare with the pieces discussed in section 2.3), although the patterns created by the data (being cyclical and seasonal) are arguably similar. I was artistically stimulated by the idea that the actions of thousands of city traders were contributing to the shape of the piece albeit unconsciously. Having made several experiments with the data and struggling to find a sonification scheme, *Troy Ounce* was a breakthrough in terms of focussing down on just one changing aspect of data (as opposed to mapping each one of the myriad data items referred to above) and using this to drive a compositional scheme that was related back to the data via means of a musical 'pun' – the use of *Gold!* - rather than an arbitrarily arrived at sound source such as a synthesised tone changing in pitch. I would explore this idea further in other pieces in the portfolio. It

1 'Web scraping' is the practice of obtaining data from websites where an official datafeed or API is not available.

was with this binding of source material to the underlying data that I first started to formulate my ideas on how the soundworld created by a piece could be artistically linked to the data driving the piece, not just in having a mapping scheme that is indexed to the data (changes in the data resulting in changes to the sounds heard) but in an symbolic – and ultimately playful – way.

Arriving at this soundworld is typical of the methodology outline in chapter 3 - having found an interesting dataset and experimented with mapping the changes in it (focusing down on the direction of the data rather than absolute values) I entered an iterative process with an element of trial and error, but also of creative inspiration (alighting on a musical pun) to attempt to discover a sound to link to the data to make a unified work.

4.2 *Ephemeris de la Lune*

Ephemeris de la Lune is a sonification of the passage of the moon.

4.2.1 Genesis and Influence

Researching the "800% slower" meme (Clayton, 2010, Richards, 2011)[2] in relation to another project, I came across a version of Beethoven's *Moonlight Sonata* which had been subjected to the PaulStretch algorithm and slowed down by 800%. This was a seductive soundworld; unlike pop records subjected to this treatment, where the results are often chaotic and noisy (mainly due to the presence of strong percussion elements), the solo piano of the sonata makes for a more coherent single sound, the attacks of the piano being stretched out into long, sustained tones.

In its use of the *Moonlight Sonata*, *Ephemeris de la Lune* represents another work where the data sonified has suggested material through a musical pun (as I had done earlier with *Troy Ounce).* Appropriation of Beethoven has pedigree in sound art itself: Leif Inge time-stretched Beethoven's 9th Symphony to 24 Hours in *9 Beet Stretch* (2004) and Luc Ferrari manipulated the 5th Symphony for *Strathhoven* (1985). Indeed. the appropriation of other artists' works (from classical to pop) is a common theme in sound art. For example, John Cage incorporated works by Mozart into *HPSCHD* (1969) and James Tenney appropriated Elvis Presley for *Collage #1 (Blue Suede)* (1961), not to mention John Oswald's *Plunderphonics* (Cutler, 2004). Writing of Leif Inge's work Brubaker (2009) refers to this practice as 'troping' (p. 141) where "a remodeling, sometimes a building within, or a new annexing to something that remains...artists today have discovered previously unimagined spaces within, scrutinizing art icons, troping through technology" (p. 141). The idea of linking a work about the Moon to the actual *Moonlight Sonata* was reinforced by my

2 The 800% slower meme is an internet meme where PaulStretch time-stretching software is used to stretch original recordings to 800% of their length, creating ambient style music from seemingly improbable sources; most notably the teen-pop singer Justin Bieber's *You Smile*, the 800% stretched version of which gained airplay in its own right on BBC Radio 6 Music (see https://www.bbc.co.uk/programmes/b00ytm0b).

becoming aware of Katie Patterson's *Earth-Moon-Earth* (2007), an installation work that takes Beethoven's *Moonlight Sonata* and transmits it as Morse code via earth-moon-earth radio transmission, during the process of which various parts of the sonata are lost as the radio signal fails to reflect from depressions and craters in the Moon's surface.

In *Troy Ounce*, the fluctuations of the gold price altered the playback of the sound file – a virtual LP – forwards and backwards. The cyclical nature of the movement of the moon through the sky over 24 hours, caused by the rotation of the Earth, allowed me to extend this metaphor, imagining the whole *Moonlight Sonata* as a giant record 'played' by the motion of the Moon, completing one cycle every 23 hours, 56 minutes (a sidereal, or astronomical day) or in LP terminology running at 0.00069rpm. However, unlike the slowed down LP records of Schaefer's practice, the phase vocoder time-stretching method means there would be no downshift in pitch.

However, I was conscious that simply time stretching the *Moonlight Sonata* arbitrarily to a day's length would amount to something of a re-tread of Leif Inge's previous work (*9 Beet Stretch,* 2004*)* and also not particularly supportive of my research. A more varied sonification scheme, taking into account more than just the movement of the moon through the sky, was required to make a satisfactory work. I took inspiration from *The Place Where You Go to Listen* (2009) where John Luther Adams chose three data points to sonify. He linked elevation (the moon's position relative to the horizon) to pitch so "When the moon is below the horizon, it has a deep bass voice. As it rises, it glides continuously from baritone, to tenor, to alto, to soprano." (Adams, 2009, p. 124). The moon's phase (the proportion illuminated) is linked to the bandwidth of a filter: "The bandwidth of this sweep varies from about a Major Third (408 cents) at the full moon to silence (0 cents), briefly, at the new moon." (Adams, 2009, p. 124). Finally, the horizontal position of the moon (its azimuth) is linked to its spatial placement within the installation (via a multi-channel speaker setup) (Adams, 2009, p. 137).

4.2.2 Technical Report

The Ephemeris of the title refers to an astronomical data table which gives the position in the sky of a celestial object on any given date and time. In the past these ephemerides were printed tables but they are now calculated by software (a Python extension, PyEphem) in real time, making the data amenable to a real-time sonification. PyEphem retrieves azimuth, elevation and phase of the moon and passes it to a Pure Data patch for sound processing.

The azimuth, which is reported in degrees from 0-360^{o}, relative to an observer (set to the longitude and latitude of my house in Sheffield; although a changeable variable, amenable to customisation according to the location of an installation) is scaled and fed into the 'pointer' value of a phase vocoder object 'stretch' (see also *Troy Ounce* section 4.1.2). As the azimuth passes from 0-360^{o} over 24 hours the file is slowly played (similar to the scheme in *Troy Ounce*, but smoothly progressing through the file at a steady rate).

The elevation of the moon relative to the observer can go between 90^{O} (above your head) and -90^{O} (beneath your feet) although extremes only occur at the equator. This property is used to choose which combination of many different Moonlight Sonatas is heard. This is another aspect influenced by Schafer's three-armed turntable (see section 4.1.1) which is capable of playing many records at once creating an instant collage.

Instead of LPs on a physical turntable, in the virtual domain this means there are 19 phase vocoder 'stretch' objects all playing at once. For easier reading, the -90^{O} to 90^{O} elevation is transposed to 0-180^{O} and 'stretch' objects are placed at 10^{O} intervals. If the moon is at 20^{O} of elevation (transposed to 110^{O}), then the 12th sound file is heard. However, the 'space' between these points needs to be dealt with. Each sound file is subject to an amplitude curve (a Hann function). So, at 15^{O} of elevation, both the 11th and 12th sound file are heard, mixed according to the values (0-1) generated from these curves. These amplitude curves allow a smooth transition as the elevation changes over time.

Depending on the phase of the moon, a mix of the 19 different sound files is being travelled through as the elevation of the moon changes. There are similarities to Adams' notion of bandwidth and filtering. A full moon produces a wide spectrum, with all sound files heard to some extent in the mix. At a new moon the mix is narrower, with a maximum of two files can be heard at any one point.

4.2.3 Evaluation

The data driving *Ephemeris de la Lune* has a unique characteristic in this portfolio: the predicability of the data. Unlike other pieces based on human activity or unpredictable natural events the ephemeris of the title is an accurate prediction based on the laws of physics and this could rule it out of being a truly generative piece (following my observations in section 2.2). However, the complexity of interaction between the position of the moon in the sky, its phases and the seasons makes it unpredictable for an audience (including me) to know what sound this work will make an any given day. As with Adams' (2009) observations about *The Place Where You Go to Listen*, the changing of the work with the seasons, over days and months is part of its appeal, not to mention the facility to change the observation point. *Ephemeris de la Lune* as run on any given day in Rio, or Sydney, would give a different result to one run in Sheffield.

Ephemeris de la Lune also stands to prove an important point in the portfolio – despite accessing the same data as another composer (*The Place Where You Go to Listen ,* Adams, 2009) – a considerably different piece has been created, by interpreting the data differently and constructing an altogether different soundworld.

Regarding my methodology, *Ephemeris de la Lune* represents a situation where a successful strategy has already been discovered in a previous experiment (the linking of soundworld to data via a musical pun in *Troy Ounce* and subjecting existing audio to time-stretching to create drones) and applied to a different dataset, nevertheless the difference in the datasets (one being random fluctuations, the other cyclical and ultimately repeating) leads to a different mapping strategy. *Ephemeris de la Lune* also represents an example of widening and deepening a successful strategy – with many more channels of stretched audio being potentially heard.

4.3 *Singing in the Wires*

Singing in the Wires is a drone piece based on sonifying fluctuations in the National Grid electricity supply.

4.3.1 Genesis and Influence

The genesis of *Singing in the Wires* arises from one of the challenges I found in creating generative works: selecting a range of pitches that could be used in a compositional scheme. Researching La Monte Young and his *Dream House* (1993-) installation from the point of view of music of infinite duration I was also confronted by an artist whose exploration of pitch has been extremely thorough. Young claims that a key influence on his life-long interest in drones was growing up in rural Idaho and listening to the sound of electricity transformers:

> The other sound that really had a big influence on me was the sound of step-down transformers on telephone poles in an electrical yard… I was also listening to the sound of these telephone poles, and it was just a continuous steady hum… (Young quoted in Zuckerman, 2002)

In reference to this experience, he named a piece *The Melodic Version Of The Second Dream Of The High Tension Line Stepdown Transformer From The Four Dreams Of China* (1984), with its constituent pitches supposedly derived from those heard in the wires.

This set me wondering whether electrical information on power generation could somehow be accessed to make a piece paying tribute to Young. Some research led me to Gridwatch (n.d) a website dedicated to the live monitoring of the National Grid (the company that manages power infrastructure in the UK) and subsequently to the raw data published by it. Conceptually it seemed to me that this should be a drone piece, the continuous sound reflecting not the continuous generation of electricity, but also serving as a metaphor for the whirring and droning of the generators themselves.

4.3.2 Technical Report

Two items of data are pulled from the National Grid data by a Python script: the current operating frequency of the grid and the current demand in gigawatts. This data is passed to a Pure Data patch for sound processing.

For demand management the electricity supply in the UK does not always run at exactly 50Hz. National Grid is mandated to keep the operating frequency within +/- 1Hz of 50Hz (when demand rises the frequency drops to allow demand to be balanced). This fluctuation suggested to me the kind of microtonal differences that composers such as Phil Niblock have exploited (in *Touch Strings* (2009) for instance). In Niblock's work, multi-layered drones (usually made up of pitch-shifted recordings of the same instrument) appear to shift in time because of the beating frequencies generated by microtonal differences. Niblock describes this method thus: "What I am doing with my music is to produce something without rhythm or melody, by using many microtones that cause movements very, very slowly." (Niblock, 2007, para. 2).

In a first draft of the piece I translated the fluctuations of the grid directly to transpositions in the source sound file but as the changes in the grid frequency are often in the order of fractions of 1Hz, this appeared to have negligible influence on the sound heard[3]. I decided to scale up 1Hz to 1 octave so small changes in the grid frequency would be audible. For example, in this scheme a change of 0.083 in the grid frequency is a semi-tone difference, although all possible microtonal fractions in the octave span are possible.

Following the example of Niblock and Young I wanted the drone to be made up of several notes, raising the question of what pitches to include. In the two previous works discussed *Troy Ounce* and *Ephemeris de la Lune* the pitched element was a function of the random assemblage of existing material. In this sonification, there would be a definite harmonic scheme. The source sound is a drone generated from a recording of a guitar E string played by a violin bow transposed down to 50Hz. Following the example Young (and John Luther Adams) I chose to make transpositions of this source sound using the 'pure' structure of the harmonic series, constructed from the base frequency of the grid at 50Hz (+/- 1 Hz).

The five-digit number representing current demand in gigawatts is transformed to make a chord. In this five digit number saw a similarity to chord notation that is written in steps (1-3-5 = a major triad, for example) and the potential for each demand figure that comes through to produce a different permutation of possible harmonics. For example, at time of writing the demand figure reads 38873, at 50Hz, a chord of 50Hz (the fundamental always sounds), 150Hz, 400Hz, 400Hz, 350Hz and 150Hz would be heard. As the data changed, unpredictable pitch and harmonic combinations would sound as the sound was modified by changes in demand (changing with the time of day, or time of year) and by fluctuations in the base frequency.

The phase vocoder object is used once more, although in this example, not so much to add time stretching (although a stretch is applied) but to exploit the ability of the phase vocoder to alter pitch without affecting duration. This allows for the large transposition required for the upper harmonics to be sounded from the original sample. The entire scheme is fed through a delay network (an example of expressing individual compositional preferences) which means the exits and entries of the transpositions slowly feed into the drone, rather than producing abrupt changes.

3 It could be argued (and would follow a La Monte Young like line) that with sufficient ear training, and a suitably meditative practice, these small fluctuations could become perceptible. There is a clear trade off between 'being true to the data' and scaling schemes toward a musical outcome.

4.3.3 Evaluation

Singing in the Wires was my first attempt to design a sonification that was not purely reliant on a 'musical pun' for its conceptual scheme, but rather had an abstract musical object (the bowed guitar drone) permuted and defined by the scheme of sonification. In some senses this was my first attempt to compose a sonification from the ground up using traditional musical materials – pitches – rather than a collage of existing materials (as in *Tory Ounce* and *Ephemeris de la Lune* previously). That is not to say there is not a conceptual element to the piece, influenced as it was by the biographical link to La Monte Young.

Singing in the Wires also represents my first attempt to 'see' something in the data that can be transformed into a musical parameter – in this case seeing the figures in the electricity demand figure, not as a sequential number (to result in a raising or lowering of pitch, or tempo, say) but 'reading' these data as if they were a set of intervals to be heard (I have jokingly referred to this as 'weird numerology').

This 'weird numerology' is an example of a methodological discovery – working playfully with the structure of data to see something with musical potential - which becomes part of my 'tool kit' when faced with similar data.

However, this 'weird numerology' is also a test of what I consider to be artistically coherent – a sonification with high indexicality (see section 2.1.3) would have pitch increasing with each step up in demand but in this scheme the transition from 39999 (a chord with the 3rd and four 9th harmonics sounding) to 40000 would actually result in the audience perceiving a lowering in pitch as the 9th harmonics (the highest sound in the piece) are replaced by the base frequency (the '0th' harmonic). Yet the artistic coherency isn't sought (necessarily) in direct indexicality, rather, I have sought to construct it in the concept around the piece, an idea that the piece is being unconsciously 'played' by the actions of millions of individuals. As their actions change, so do the sounds heard.

From a methodological point of view *Singing in the Wires* gives one of the clearest examples of the iterative process of auditioning the material and adjusting how the data is dealt with (the transposition so that 1Hz covered 1 octave described above) to arrive at an artistically satisfying result, whilst attempting not to make completely arbitrary decisions and remain 'true to the data' and retain a coherent link between changes in the data and sounds heard.

4.4 *The Beach Buoys*

The Beach Buoys is a drone piece based on wave data collected from buoys placed on the California coast.

4.4.1 Genesis and Influence

In my previous work *Playing the Weather* (2010) I had approached the sonification of data from the point of view of *one place-many data parameters.* So, the sonification scheme relies on choosing a location and then the data from the weather parameters – temperature, wind direction, pressure and so on are mapped and sonified (higher temperature: higher tempo for example in that piece). In the course of looking for sources of weather data to drive that piece I found a data source from ocean-deployed sea buoys (CDIP, n.d.) but I discounted them as the data they produced was too slight and too uninteresting, mostly consisting of just two parameters: an average wave height and period in seconds.

I began to see the possibility for working the other way round: *one data parameter but many places.* The resulting sonification is an aggregate of many small elements placing the listener in an 'omnipresent' role, hearing the aggregation of data over vast distances. In this manner many sea buoys, even if they are just reporting wave height and period, begin to act in concert as individual elements in a large sound mass.

This sound-mass approach was influenced by Ligeti's massed 'micropolyphony' in works such as *Atmosphères* (1961) and demonstrated in *Poème Symphonique* (1962). This approach is characterised by the massed sound of individual parts changing in time[4]. It also pays homage to Xenakis' *Metastasis* (1955) or *Pithoprakta* (1956) where instruments, following their own independent part, contribute to an aggregation of sounds producing what Xenakis termed a 'totality'. In *Formalized Music* (1992) He explains:

> …natural events such as the collision of hail or rain with hard surfaces, or the song of cicadas in a summer field. These sonic events are made out of thousands of isolated sounds, seen as totality, is a new sonic event. (Xenakis,1992, p.9)

4.4.2 Technical Report

The soundworld for The Beach Buoys revolves around another musical pun (see *Troy Ounce* and *Ephemeris de la Lune*). To generate a massed sound analogous to a wave I decided I wanted something sustained and I thought of a choir of voices. The Beach Boys, with their timeless association with the ocean provided another musical pun and jumping off point. By taking several sustained chords from a vocals only mix of *You Still Believe in Me* (1966) I was able to create a choir-like source sound.

The data used is collected by sea buoys deployed by the CDIP (Coastal Data Information Program) at the University of San Diego. This data is collected by a Python script which is then sent to a Pure Data patch for sound processing.

The buoys routinely report the average wave duration in seconds; large, rolling swells can last up to

4 Ligeti coined the term 'Meccanico' (*mechanic or mechanical)* to describe this interaction of small parts).

15-20 seconds, faster waves around 5-8 seconds. It is the variance in wave period between different buoys (a total of 10 are sonified) that provides a tapestry of overlapping periods. These overlapping – but unpredictable – periods are reminiscent of the “incommensurable loops” (Eno, 1996b, para. 15) that characterised Brian Eno’s early generative scheme for *Music for Airports* (1978). However, the loops in this case are all of the same source sound rather than different tones, or instruments. Thus a more homogeneous, gently moving mass results. A series of phase vocoder 'stretch' objects loop the choir sound, playing it for the duration specified by the wave period.

The source sound is further transformed by the sonification of another set of data reported by each buoy. Each buoy provides an analysis of current wave activity expressed in terms of a Fast Fourier transform (FFT) – where the energy content of the wave is measured in frequency bins, in the same way FFT is used to analyse audio (although the frequency bins in wave analysis are mostly infrasonic). It is this FFT data that Strum (2003) used in his sonification of this data using an audification (see section 2.1.2) approach, bringing the wave frequencies into the audible range. Looking at the wave spectrum on a graph suggested a different compositional approach to me. The wave shape is translated into a filter curve, so what we hear of the original sample is transformed by the sea state at that moment. Each part of the FFT data (64 bins) is scaled to 0-1 and then fed into an FFT filter (an adaptation of a design by Kreidler, 2009). Despite using the same source material, each channel is given its own sonic identity.

4.4.3 Evaluation

The homogeneous, moving mass of similar tones is an attempt to inculcate artistic coherence by drawing a successful sonic analogy with the ocean. The sound mass seemed the most appropriate response to data corresponding to the movement of waves in the ocean. Where the sound masses of Ligeti and Xenakis cited in the opening section were characterised by eventual dissipation and resolution (being time-bound orchestral pieces), the sound mass produced by The Beach Buoys is characteristic – emblematic even – of the infinite approach described in section 2.2.3. The mass simply goes on and on, subtly changing with shifts in the seasons, reflective of the infinite, unceasing nature of the ocean.

From a methodological point of view *The Beach Buoys* went through several iterations trying to find the right sound material: it was an idea without a sound for some time. I experimented with filtered white noise which felt like too literal a linkage (synthesised sea sounds often start with a noise element). Having used musical puns previously I was reluctant to use an entire Beach Boys song in the same way the *Troy Ounce* or *Ephemeris de la Lune* had done. Finding a suitable small fragment of the Beach Boys took some time (the percussive elements of full band performances do not sound so graceful or sea-like when subjected to time stretching). Having already worked extensively in the time domain by time-stretching material the idea of filtering it and working in the frequency domain, based on parameters in the data opened up new ideas which would be repeated later on.

4.5 *Singing Wikipedia*

Singing Wikipedia takes the vast and ever changing corpus of Wikipedia as its libretto, sung by an electronic choir of computer generated voices.

4.5.1 Genesis and Influence

Singing Wikipedia was partially influenced by John Cage's works such as *Song* (1976) where a text (in this case the Journals of Henry David Thoreau) is submitted to random chance procedures to produce a randomly constructed libretto. In a recording available at UbuWeb (n.d.) Cage performs the work by reading from this reconstructed text (Cage, 1976). Cage also used random excepts from Thoreau to produce Song Books (1970) and Empty Words (1974), a "a 10-hour monologue (plus breaks) that consists of displaced phrases, words, syllables, letters and sounds drawn by chance operations from the Journals of Henry David Thoreau (Tuck, 1981). Although Cage's use of a vast text (some 7000 pages, 2 million words, "About the Journal of Henry David Thoreau, 1837-1861", n.d) produced a long work, it was not an infinite work (see discussion in section 2.2.3). Even if Cage's chance procedures were arranged so every word in the journal were randomly rearranged in a non-repeating sequence, the work would eventually[5] reach a conclusion.

The pieces described so far in the portfolio have exploited the ever-changing nature of a data stream to provide the 'generative' element of the work. The problem with accessing a text such as Thoreau's Journals or the Complete Works of Shakespeare is the fixed nature of the source 'data'. Wikipedia, in contrast, presents an ever changing corpus to draw on. I heard an interview with Wikipedia's founder Jimmy Wales talking about the growth of Wikipedia with impressive statistics about the number of articles added every day, the number of edits per minute and so on. Given Wikipedia's encyclopaedic approach and open platform, in theory, it will keep growing as long as human knowledge continues to grow. The mutable nature of each Wikipedia entry means the whole 'text' of the encyclopaedia is never fixed at one point. Thus, in Wikipedia I have a text analogue of the ever changing data that has driven previous pieces.

A simple version of this piece would be the computerised voice endlessly reading through Wikipedia articles. The use of a computer voice (text-to-speech, or 'tts') is both practical (allowing continuous performance unencumbered by human endurance) whilst also recalling the computer HAL singing *Daisy Bell* in Stanley Kubrick's *2001: A Space Odyssey* (1968) (itself based on Max Matthews, John Kelly and Carol Lockbaum's IBM 7094 experiment in 1961 see Radovic, 2008) and Radiohead's *Fitter Happier* (1997). However, in conceiving the piece wanted something more choir like – for Wikipedia to be 'sung'. This was in part influenced by my participation in the Juxtavoices choir, where 'found' material often provides the raw material for sung improvisation (e.g *Guardian Weekend Remix,* 2015) , and in part a desire

5 Taking, for example, Cage's slow, deliberate delivery in the aforementioned recording of Song (approx. 60 words per minute) going over the 2 million words of the journal would take approximately 24 days of reading, 24 hours a day.

to create something distinctive from the John Cage pieces that influenced it. The aesthetic was also influenced by the choral works of Ligeti (e.g. *Lux Aterna*, 1966) characterised by slowly changing ‘clouds’ of tones.

4.5.2 Technical Report

Singing Wikipedia consists of a Python script which accesses and processes randomly selected Wikipedia articles via the url https://en.wikipedia.org/wiki/Special:Random. Through the use of some user-defined options just the first portion of the article (the short encyclopedic entry) is used. Python further manipulates the text by locating vowels and extending them by a random amount, so 'the' becomes 'theeeee', or 'shoe' becomes 'shooooooeee'. This has the effect of lengthening the vowel sounds (to be more like singing) when this text is processed by an application called *espeak* into a sound file of the computer voice. To produce a 'mixed choir' the text is read out in several built-in voice variations (six male and five female, with varying characteristics such as fundamental pitch, pitch variation and speed of delivery).

A Pure Data patch handles the further processing of these text files into two 'choirs' in a flip-flop arrangement. As one choir is singing, the file processing for the other is going on in the background. This allows the piece to sound continuously. To achieve a choir like sound, the text to speech files are subject to time stretching (via a phase vocoder object similar to other pieces in the portfolio). This changes the spoken quality of the original files into a singing-like texture.

The harmony of the choir is based on data directly from Wikipedia. The Wikipedia API provides a live feed of the current statistics on the size of the Wikipedia corpus[6]. Similarly to *Singing in the Wires* (see section 4.3) the article count is read as a series of intervals of a pentatonic scale over two octaves. Seven digits are spread over the eleven voices of the choir with a pitch shift applied to bring that voice to the requisite pitch in the scale.

The starting pitch of the scale is further manipulated by the 'Wikipedia Fundamental'. This is the pitch at which Wikipedia is running. This is based on an idea from John Luther Adams' *The Place Where You Go to Listen* where drones are based on the fundamental frequency of the Earth (24.27Hz). Adams derives this by taking “the daily rotation of the earth, transposed into the range of human hearing. One rotation of the earth (one cycle per 864,000 seconds) transposed up twenty-one octaves” (Adams, 2009, p.120). The 'Wikipedia Fundamental' is arrived at by calculating the number of articles divided by the number of seconds that Wikipedia has been online (since 15th January, 2001). This produces a small number that can be scaled 12 octaves to musical-range base pitch (approximately 44Hz at time of writing). Given the constantly

6 https://en.wikipedia.org/w/api.php?action=query&meta=siteinfo&siprop=statistics&format=json
As I type the current statistics are: Pages:43056992, Articles:5475623, Edits:909396946

changing nature of Wikipedia as users make edits, both the chordal structure of the piece and its fundamental frequency are in constant flux.

4.5.3 Evaluation

Like *Singing in the Wires* before it, I was attracted to a sonification that was made up of data created by human actions (as opposed to other works utilising data generated from natural processes). Thousands of Wikipedians are co-creators of the piece as the corpus of the online encyclopedia are created and edited. The encyclopedia both provides the raw material to be sonified (the articles themselves) and the actions (unbeknownst to them) of editors drive the pitches of the piece.

Singing Wikipedia represented an experiment in two areas. Firstly, the use of speech tested Kramer et al's (1999) exclusion of speech from sonification, although in this case the speech is distorted through time-stretching as to be unintelligible, the vowel and consonant sounds representing raw sonic material. Secondly, *Singing Wikipedia* binds data and subsequent sound together – unlike previous pieces there is no reference to an external sound source. The data, voiced through electronic means, is the sound. Arguably, *Singing Wikipedia* is part audification (see section 2.1.2), bringing previously mute data into the audio realm with minimal intervention. However, the manipulation of the real-time statistics to generate chords around a 'Wikipedia Fundamental' are parameter mapping.

S*inging Wikipedia* is an example of re-utilising an already discovered method. As mentioned in section 4.3.3 the idea of 'reading' a large number as a set of intervals or harmonics became part of my toolkit and when presented with the article count in the Wikipedia statistics I reused this method (although as intervals of a different pitch series). Methodologically, *Singing Wikipedia* also sent me on the path to discovering a new way (new to the portfolio) of articulating data in sound (peculiar to this piece, being text rather than numbers) via voice synthesis (as opposed to manipulating musical material via sampling).

4.6 *Currency Wars*

Currency Wars is sonification of international currency exchange markets between eight currencies.

4.6.1 Genesis and Influence

When looking at the financial data on the web, one of the most striking things about currency exchange rates is the frequency of their change. There is an archetypal image of the financial exchange where banks of computer monitors show the flickering of red and green as currencies, stocks and commodities rise and fall in price. It is this rapid change that the soundworld of *Currency Wars* attempts to reflect.

The currency markets are displayed as 'pairs' or 'crosses' e.g. pounds sterling vs US dollar, known by three letter acronyms or initialisms separated by a slash e.g. GBP/USD. This 'opposition' of currencies gave rise to the concept for this piece, with the idea of an 'oppositional' piece partly inspired by Xenakis' use of game theory in *Duel* (1959) and *Strategie* (1962). In those pieces separate groups play modules of sound chosen by separate conductors, having the effect of periodic blasts of sound from different parts of the orchestra.

In *Troy Ounce, Ephemeris de la Lune* and *The Beach Buoys* I had alighted upon a technique of using a pre-existing piece of music that had a conceptual connection to the data used to structure the piece. What sources would stand for currency? I took further inspiration from the 20th Century canon, recalling Stockhausen's *Hymnen* (1967) and its use of national anthems. Each currency would therefore be represented by its national anthem (for the euro, the official European Union anthem based on *Ode to Joy* is used).

4.6.2 Technical Report

A Python script 'scrapes' live currency data from a currency trading webpage. For eight major currencies[7] there are 56 possible pairings and 28 unique pairings. A separate Python script runs for each currency and its possible pairings and passes data to a Pure Data script to handle sound processing.

The currency on the left of a pair e.g. USD/CHF (US dollars to Swiss francs) is determined by the Python script to be either 'up' or 'down' relative to the currency on the right. This triggers a random segment of the national anthem of the currency that is dominant at that point in time (the 'oppositional' idea taken from the Xenakis pieces). The magnitude of change is also calculated and linked to the envelope of the sound: a small change produces a sharp attack; with larger values there is a slower, more gradual onset.

Each currency is assigned a channel (spread of stereo for the purposes of demonstration, although amenable to multi-channel presentation). If, in our paired example, the US dollar is up against the Swiss franc when the data is polled, a short blast of the Star Spangled Banner is heard in the US dollar channel, but also the Swiss franc channel too (as the reciprocal).

4.6.3 Evaluation

Like other pieces before it *(Troy Ounce, Singing in the Wires, Singing Wikipedia) Currency Wars*

7 Major trading currencies are: pounds sterling, US Dollars, Canadian dollars, Swiss francs, the euro, New Zealand dollars, Australian dollars and Japanese yen.

sees a fascination in sonifying human activity (rather than natural phenomena) and bringing the huge aggregate effort of thousands of currency traders to bear in co-composing the piece.

At this point in the portfolio, the methodology of selecting audio sources related to the dataset was firmly established as a strategy. However, as *Currency Wars* shows the way this audio is mapped to the data can still present opportunities. Whereas in previous pieces time-stretching had been applied extensively, essentially taking a small amount of material and stretching it into large drones, in this piece the process is reversed with a large amount of source audio fragmented into tiny parts. This is a result of scrutinising the data (and how that data changes in time) and working towards a soundworld which accurately reflects it.

The main contribution to the portfolio of *Currency Wars* to my argument is its attempt to reflect the character of the source data (this could be considered 'being true to the data' see section 2.1.5). The skittering, rapidly changing nature of the data calls for a skittering, scatter-gun soundworld; just as in *The Beach Buoys* an attempt is made to find a slowly changing sound analogy for the ocean in *Currency Wars.* The concern is to arrive at a sonification which accurately reflects the underlying data.

4.7 *In Flight Music*

In Flight Music is a sonification of air traffic data from aeroplane transponders. The number and movement of aeroplanes in the sky permutes changes in an organ drone.

4.7.1 Genesis and Influence

In Flight Music continues a theme explored in *Singing in the Wires* and *Currency Wars,* being concerned with data created by the actions of humans, rather than natural processes (*Ephemeris de la Lune*, *The Beach Buoys*).

In Flight Music, like *Singing in the Wires,* partly flows from stumbling upon a dataset and wondering if a piece could be made from it, although having discovered the OpenSky data displaying live flight information relatively early on in the process of putting together my portfolio, I didn't know yet what piece to make from it.

The genesis of the piece also lay in my intention to make a work that falls somewhere between the character of earlier pieces. In *Singing in the Wires* and *The Beach Buoys* the sound is continuous and unbroken, just like the flowing of electricity from the National Grid, or the movement of the oceans, which data they represent. In *Currency Wars* the sound world is unpredictable and fragmented; chaotic even. After seeing a performance of Morton Feldman's *Crippled Symmetry* (1983), I began to wonder if there was a data source that would drive fleeting events and my earlier discovery of OpenSky came to mind. The presence of aircraft overhead is fleeting; this is music with entrances and exits.

The mass of aeroplanes flying above our heads put me in the mind of *Cloud Music* (Watts et al, 1974-1979 see section 2.3.3), with sound events triggered by objects moving through the sky. The graphical representation of the aeroplanes (on the OpenSky website) moving around also suggested brought to mind *Pithoprakta* (1956) by Xenakis, with its individual molecules of sound moving according to rules of Brownian motion and individual sound events making a large sound mass.

Around 4000 aircraft are tracked at any one time on OpenSky but producing 4000 different sounds was not in my plans for the piece (although this is feasible, given the resources). Playing with the live map part of the OpenSky website, zooming in on Sheffield, the answer to a more manageable scheme became clear. It was simply a matter of narrowing down the focus.

I conceived the aeroplanes working in a three-dimensional grid, bounded by a 'view' over the map, a set number of square miles with Sheffield in its centre. The aircraft's latitude (y), longitude (x) and altitude (z) would be mapped to a sound, so that as a one moved over the grid the sound would fluctuate until it went 'off the map'.

At times there could be many aeroplanes 'in view' and a rich sound world would be produced, for periods there could be just one, or none. I started to think about the piece in terms of the possibility of long periods of Cagean silence; a high contrast between musical events and their anticipation. This stands in contrast with other pieces in the portfolio that are constantly sounding (although given a different centre point – a busy airport city such as Frankfurt, for example – the sound world would be different)

I was also conscious that at this point in the portfolio the associative sound source (*The Moonlight Sonata*, *Gold!*, national anthems) was in danger of becoming a cliché. I wanted to branch out and use an original source sound, composed for the purpose. Thus, the soundworld of *In Flight Music* was influenced by two pieces. Firstly, Jon Gibson's *Cycles* (1977), an improvisation for pipe organ characterised by slowly building and modulating chords, and secondly Howard Skempton's *Lament for Organ* (1972) where a set of chords is slowly and gradually modulated. In both pieces the entrances and exits of notes is just perceptible and there is a satisfying tension between stasis and movement.

4.7.2 Technical Report

Data is sourced via the OpenSky Network (n.d) website, a collection of volunteer enthusiasts running a sensor network that monitors air traffic via the publicly accessible tracking system for aeroplanes (ADS-B). Via their API the public are able to access what amounts to an air traffic control system (albeit one limited by the range of the sensor network, and to publicly available data) The OpenSky API makes data retrieval of all aeroplanes currently tracked simple. All data for any currently tracked aircraft can be queried – heading, altitude, speed, latitude and longitude.

A Python script accessed this API and filters data down to a 'scan' area – 1° of longitude and latitude around Sheffield. Having identified the area to 'scan' the Python script runs on a loop, retrieving the current plane states at 15-second intervals (the data is not updated any more frequently than this). Latitude, longitude and altitude are logged. For new aeroplanes a new entry is started; for currently tracked planes the values are updated and for aeroplanes now out of the 'scan' area, the record is removed.

In Flight Music occupies a new niche in the portfolio, that is the data it is sonifying is of arbitrary number. What I mean by this may be easier to illustrate in contrast with another pieces. In *The Beach Buoys* the number of buoys to be sonified stays fixed – there are 10 channels of sound at any one time. Even though the sound world of *Currency Wars* is fairly chaotic there are 8 channels, one for each chosen currency. *Singing Wikipedia* has a fixed 'choir' of 11 voices. With *In Flight Music* the number of simultaneous channels, or voices, is arbitrary; depending on the number of planes 'visible' at any one time. At times the piece can be dense, polyphonic, then die away to just one voice.

The arbitrary nature of *In Flight Music* means my customary architecture of a Pure Data patch to handle sound processing is replaced with a SuperCollider engine. Supercollider's flexible approach means that once a synth (analogous to the patch in Pure Data) has been defined an arbitrary number of instances of these synths can be created.

Each aircraft tracked is assigned a synth based on granular synthesis with the parameters gleaned from the aircraft (latitude, longitude and altitude) corresponding to the position in a sample that the grain is taken from. In line with my citation of Gibson's *Cycles* (1977) above, the sound source is a sustained organ chord.

This chord is the 'Hendrix Chord'[8] or dominant seventh sharp ninth: it's unresolved, floating quality suited being layered several times and being built up over time and change without seeming to resolve. Over the course of the source file, this chord is built up adding an interval each time then, at the middle of the file the full chord is voiced, then each interval is taken away again in turn. The chord is played in C (on the x axis, an aeroplane's longitude) and F (on the y axis, an aeroplane's latitude). The z axis (an aeroplane's altitude) features single notes from both chords played as a scale. The net result is a constantly changing chords – based on the notes in the source chord - depending on where planes are on the map at any one point. For example, an aircraft in the far corners of the map would result in mostly a perfect fourth being heard (the root C and F components of the chord). An areoplane approaching the centre of the map results in a huge compound chord made up of all the intervals of both voicings.

8 So called due to its employment in Purple Haze (1967), the learning of which was something of a rite-of-passage for a young guitar player.

4.7.3 Evaluation

In Flight Music like *Singing in the Wires* is an example of a piece where the sound (an organ chord) is only abstractly related to the source data. It is an instance of what Gresham-Lancaster and Sinclair ((2012, p. 68, see section 2.1.2). termed Re-Mapping, where an existing source is 'perturbed' by changes in the data. Where other pieces have employed musical puns (*Troy Ounce, Ephemeris de la Lune, The Beach Buoys)* or even attempted to make sound from the data directly (*Singing Wikipedia)* there is nothing to explicitly conceptually link the organ sound in *In Flight Music* to the source data.

Where, then, do I start to build the 'artistic coherence' of the work? *In Flight Music's* contribution lies in its exploration of how to sonify data of arbitrary size. At any point (and depending on initial parameters) there can be tens, hundreds of individual sound events contributing to the mass, or none at all. The sonification scheme had to be amenable to these conditions. Unlike the constant (yet slowly changing) drone of the sea, sonified in *The Beach Buoys,* the drone of *In Flight Music* comes and goes, hopefully reflecting the experience of watching (and hearing) aircraft passing overhead.

As commented in section 4.6.3, the strategy of using musical puns was becoming a well-worn strategy within the portfolio. *In Flight Music* represents something of a methodological experiment in using an abstract - although not necessary arbitrary – sound source. There is still an attempt to find a sound appropriate to the data through musical experimentation and inspiration. As described above, the nature of the dataset which can represent and arbitrary number of data points at any one time necessitated a methodological change in terms of the of the sound creating architecture. A pivot toward using SuperCollider facilitated serving this type of data source.

4.8 *Protest* Songs

Protest Songs is a sonification based on the UK government's petitions site, where members of the public can suggest topics for parliamentary debate.

4.8.1 Genesis and influence

Protest Songs represents, once more, a piece where the availability of certain data has come to my attention and I have set about envisaging a piece which could be served by that data. When I discovered the live data feed from the petitions website (petition.parliament.uk, n.d) I thought of a piece punning on the idea of protest songs[9] and a piece that would bring voice to the current feelings of the nation unique to that point

9 A term that gained currency (first in USA) in 1960s for song that voiced feelings of protest about some social or political injustice

in time[10]. Like other works which have focused on human activity, I was fascinated by the idea of bringing all the disparate signatories to these petitions to one soundspace.

Having worked with the computer generated voice in an earlier work in the portfolio (*Singing Wikipedia*) I became interested in further exploring the contradiction of using speech audio in a sonification, running counter to Kramer's foundational definition (Kramer, 1994 and Kramer et al, 1999, see section 2.1.1) where speech is specifically excluded. Like *Singing Wikipedia* this work was also partly influenced by my participation in Juxtavoices, an 'antichoir' which frequently uses found text and the spoken word as the basis of its work e.g. *Guardian Weekend Remix* (2015) which uses layers of spoken word as a foreground among more textural vocal devices. It would be impossible not to cite Hansen and Rubin's *Listening Post* (2002), a sonification of internet relay chat, as an influence; in particular, their use of the robotic synthesised voice and their "attempt to convey the scale and content of thousands of conversations in real time." (para. 25)

The overarching concept is to sonify the idea that somewhere, somebody is signing up to this idea, digitally nodding in agreement, every second: that the sounds heard are the consolidation of activity on the petitions website, just as the sounds of *Currency Wars* or *Troy Ounce* are the sum of all the activity of thousands of city traders. Although speech audio is used and is on the whole intelligible, the intention is that the words form a texture, rather than fulfil a strictly information-giving role. It's hoped that the listener hears a sort of litany, noting repetitions, hearing differences. This litany analogy is also made by Hansen and Rubin who state "The layers of pitched voices take on the quality of a chant or litany" (quoted in Modes, 2014, para. 48). The soundworld is further detailed with an extra layer of concrete sounds from real protests.

4.8.2 Technical report

There are three simultaneous layers to the piece. The first is the simple reading-out of the petitions (the litany described above). Like Singing Wikipedia this is achieved via the espeak voice synthesiser. A Python script parses the json feed from the petitions.gov.uk site and determines which petitions have been recently signed. For each petition that has changed, a line is written to a batch file with the espeak command and variables (voice, variation) and the title of the petition. When all the petitions to be rendered have been processed, the batch file is executed, meaning a series of espeak commands with different voice properties will be executed and the petitions read out by the synthesised voice. Having been executed the Python script runs again, looking for further updated petitions .

Meanwhile, a second element provides a background texture based on random slices of the petition

(Rutherford et al, 2013)

10 For example, in early testing, the England football team were entering the later stages of the FIFA World Cup and a petition to make the day after the final a bank holiday should England prevail became very prominent in the readings, soon to fall away when the team were eliminated in the semi-final.

voices. In parallel with the espeak voices being rendered live, they are also rendered into a bank of eight sample berths. These eight samples are divided into small slices and played (this is reminiscent of the type of instruction that might be given in a Juxtavoices score, to freely improvise with fragments of a text). The tempo at which the slices play is governed by the number of petitions signed per second. More petitions signed equals a higher tempo.

The third element takes a sounds of actual street protests (sourced via freesound.org, n.d). The sounds were divided into ‘active’ and ‘ambient’ categories. The samples play on a loop with a crossfade between them. An ‘anger index’ (the number of petitions signed between runs of the Python script) governs how far toward the ‘active’ the crossfade travels. At low anger indices (c. 1-4) mainly ambient sounds are heard. There are four channels of these crossfades, so that an anger index c. 20 would mean all active samples playing cacophonously.

4.8.3 Evaluation

Like *Singing Wikipedia* before it, *Protest Songs* is an example of the data (the petition) becoming (at least part of) the sonification. Although Kramer's et al's seminal definition of sonification ruled out speech, artistic sonification can employ voices not necessarily for their information-conveying properties (although unlike *Singing Wikipedia* it is certainly possible to discern what voices are saying in this piece) but for the soundworld created.

Other pieces in this portfolio (*Troy Ounce, Singing in the Wires, Currency Wars, Singing Wikipedia*) have been interested in the rhythms of data created by human activity. However, the actions of individuals are hidden within the aggregate character of the data in those pieces. The demand placed on the electricity grid is summed up as one number, albeit made up of millions of individual actions. Likewise the movements of the money markets in *Currency Wars* are the actions of thousands of traders. In *Protest Songs,* in the vocal layer, each voiced petition is the product of an individual action. The piece attempts to respond to the data and construct its artistic ideas around evoking the idea of many voices, all over the country, agreeing with the sentiment of each protest and bringing them together into one soundspace. This is notwithstanding the other layers of the piece (the field recordings layer) working on an aggregate basis.

Methodologically, *Protest Songs* provides another example where a successful strategy (generating text to speech via espeak) is re-employed but also repurposed to the requirements of that particular piece. Likewise the idea of fragmenting the speech into a texture employed some learning from constructing *Currency Wars. Protest Songs* also served as an experiment (to be refined later on) in working in distinct layers. Previous works (*e.g. The Beach Buoys, Troy Ounce)* had been built up of multiple layers of the same material (although addressing different parts of the data being sonified). In contrast *Protest Songs* contained distinct parts with contrasting sound sources.

4.9 *Notes from Underground*

Notes from Underground is a piece based on live data from the London Underground. Arrivals at a chosen station (or stations) are used to create a tapestry of field recordings from the underground itself.

4.9.1 Genesis and Influence

Several of the pieces in this portfolio have focused on data produced by human activity. In doing this such pieces use sonification as a kind of rhythmanalysis (see section 2.1.4), where the hidden rhythms of everyday life are brought to our attention (a variation on the artistic themes discussed in 2.1.6). The operations of transport systems have been the subject of sonification before (Parviainen's *Real-time sonification of the Helsinki tram system* (2017) and Chen's *Conductor: the sound of the New York subway* (see Van Raansbeeck, 2017).

For the soundworld of *Notes from Underground* I decided to take an alternative tack to that on *In Flight Music* – instead of an abstract relationship (aeroplanes to organ chords) a musique concrète approach is taken with the sounds in *Notes from Underground* taken from personal field recordings of tube journeys (featuring a mixture of announcements, platform ambience and sounds of trains themselves).

4.9.2 Technical report

Data is sourced from the Transport for London API (Transport for London Unified API, n.d). For a selected station, the live arrivals data, which would populate an arrivals board is available giving details of each train and its expected time of arrival (in seconds). This data is polled periodically by a Python script, each train is updated with arrived trains falling out of the dataset and new trains are added as they come 'within range' (approximately 20 minutes away).

Each train is assigned a three-digit ID number (e.g. 020, 102, 210). As with other pieces such as *Singing in the Wires* and *Singing Wikipedia* these numbers are used to create a set of chords (my 'weird numerology'). However, unlike those pieces where the numbers directly relate to pitches, in *Notes from Underground* the 'harmonics' are samples from three banks (ten samples for each digit, 0-9). These, as described above, are from field recordings made on the underground itself. They are grouped into three themes.

1. Voices (e.g. station announcers, automated voice messages)
2. In Motion (e.g. trains passing, engines, brake noises)
3. At Rest (e.g. station hubbub, idling trains, doors slamming)

Thus any train garners a unique 'chord' of sounds. A train with the ID number 256 would have sample number 2 (counting from 0) from the 'voices' bank (a station announcer informing of planned engineering), sample 5 from 'in motion' (the ascending synthesiser-like sound of a tube train's electric engine) and sample 6 from the 'at rest' bank (voices on a platform).

Each train is assigned a SuperCollider instrument, controlled by the Python script (a similar mode of operation to *In Flight Music).* As noted in the write up to that piece (section 4.7.2), this exploits the ease with which SuperCollider allows arbitrary numbers synths to be 'spawned'. The SuperCollider synth consists of three granular synthesisers, taking the field recording samples as their input. Each sample's pointer is moved through the sample based on the current estimated arrival time, producing a sort of irregular, accelerating time stretch. This accelerating time-stretch was influenced by Carl Stone's *Shing Kee* (1986).

To simulate trains getting closer to the imaginary centre point of the station the sound files themselves are hard coded with an exponential fade. The effect is to 'fade in' each train as it gets closer to the station and the granular synthesiser's pointer approaches 1.

4.9.3 Evaluation

Like *Protest Songs, Notes from Underground* questions whether the idea of association between data and sounds can be taken to extremes of representation and source a sound directly related to the underlying data (the extreme analogic end of Kramer's continuum, where the sound is directly denotative - see section 2.1.3 and Walker and Nees (2011, p. 14). Rather than rely on an association or pun (as with previous pieces such as *Ephemeris de la Lune* or *The Beach Buoys*) the data and sound are from the same source (approximately). Naturally, the approach which prevailed in these previous pieces could have been applied (selecting songs which reference the tube or underground) but those avenues had already been explored. *Notes from Underground* stops short of being completely anecdotal (in the manner of Luc Ferrari's *Presque Rien* (1967-70), for example) in that the underground recordings are modified by a granulation process.

In using this sound source, the cherished property of sonification, the idea that inaudible phenomena can be rendered audible (see section 2.1.6), is brought into focus. *Notes from Underground* takes a sound source that is clearly audible to anyone taking an underground train journey (and as I explain above this existing rich soundworld is a key inspiration behind making the piece). What is made audible through the sonification, however, is potentially the totality of activity in the underground network at any one time. When the patch is launched all arrivals to a station become the subject of the sonification, putting the listener into a sort of omnipresent position. Given enough resources all stations on the network could be sonified.

Notes from Underground presents another example of methodological learnings being recycled – like the data used for *In Flight Music,* the data produced by the TfL API can be of arbitrary size. Through producing *In Flight Music* a strategy for dealing with such data already existed (via SuperCollider's ability to spawn multiple versions of the same synth). However, despite the same broad strategy being employed, the detail of the piece (especially the soundworld) depends on the source data and my response to it.

4.10 *Squally Showers*

Squally Showers is a sonification of the shipping forecast produced by the UK Meteorological Office which gives mariners details of wind, visibility and weather conditions over 31 coastal areas.

4.10.1 Genesis and Influence

The data contained in the shipping forecast is best known as a radio programme broadcast four times daily in the UK. Although now outmoded by modern meteorological data devices available to sailors, the shipping forecast remains a fixture of the BBC Radio 4 schedule and enjoys a significant cultural resonance. As Carolan (2011) puts it "[the shipping forecast has] a very strange status that is unprecedented for a weather bulletin. It has become engrained as a part of British culture".

The shipping forecast felt like fertile, although crowded, ground for an artistic response (the forecast has featured in song lyrics, poems and other media such as literature and photography). What attracted me most was the idea that through a sonification of the data in the forecast, the linear reading of the forecast could be collapsed into one single moment, with a listener placed in the centre, surrounded by the conditions being reported around the British Isles. Also ripe for exploration were the instantly recognisable sonic markers of the forecast – the area names intoned by radio announcers and the common phrases "squally showers, moderate, good", and the music *Sailing By* which plays before the day's last forecast.

4.10.2 Technical Report

A Python script accesses the shipping forecast as published by the Met Office and translates the parameters of wind speed, sea conditions and visibility into parameters for a Pure Data patch. The patch comprises several layers that make up the piece.

An ongoing drone is based on a time-stretch of the shipping forecast 'theme song' *Sailing By* (composed by Ronald Binge in 1963) – this piece of music is heard before the 00:48 broadcast and serves two purposes – as a recognisable ident allowing sailors to tune to BBC Radio 4, and to fill the time between the end of the news bulletin at 00:45 hours allowing the forecast to begin at precisely 00:48. It also serves two purposes in my work, its inextricable link with the forecast itself (see Jefferson, 2011, p. 81) provides the kind of context that I've used elsewhere in the portfolio where existing source sounds in the form of recorded music and the source data are related *(Troy Ounce, The Beach Buoys, Ephemeris de la Lune),* and the lush sonority of strings and flute provide sonic interest when subject to time-stretching. The 'organ stops' sub-patch features 12 versions of *Sailing By* with each subject to a time-stretch at different rates correlated to the wind speed as reported by the forecast as Beaufort scale numbers. A wind speed of 1 has the time-stretch progressing at its slowest (taking a full six hours) and each subsequent Beaufort scale number is a division of this, up to 12 (hurricane force) which progress at six hours / 12 (30 minutes). Each of these twelve versions are also subject to a transposition, moving from the most consonant (octave, perfect fifth) to dissonant intervals (minor second, the tritone) based on a Consonance-Dissonance algorithm developed by Foster (1995). The 12 sounds are treated like organ stops with each stop being 'pulled out' (increasing in amplitude) in a sequence determined by the wind speeds (in the case of a single value, the sound remains fixed on one stop). Thus a shipping forecast reading of "5 or 6, 3 later" for an area would result in stop 5 sounding to begin with, gradually shifting to 6 then finally 3 (the Python script creates an envelope dividing six hours between the number of reported Beaufort scale numbers).

A second layer features BBC announcers reading the forecast in a sort of chant. The depth of this chant is determined by the sea state. Calm seas (slight, moderate) result in a 'shallow' range of speakers, where rough seas mean up to 24 different voices. There are eight sea states possible, at the calmest end of the scale three voices are heard at intervals of 10 seconds; where at the roughest 24 voices are heard at intervals of three seconds. Reverb is added in greater amounts according to the visibility, so in poor visibility only a reverberant haze of the original voice is heard. As with the organ stops these chants are fed through the same filter, being determined by visibility.

A third layer is made up of the sound of ships bells. There are two bell sounds, which are triggered by Morse code patterns for each area name, one bell sample for dot and one for dash. This Morse code is cycled through at a tempo determined by the wind speed in that area (each shipping area has a set tempo based on 10 seconds plus the number of letters in its name – the tempo for Lundy would be 15 – this is divided by the wind speed as per the Beaufort scale so the faster the wind the brisker the tempo of the ships' bells.

A final layer is based on the broadcast of the forecast itself. Using a utility called 'get iPlayer' the actual latest forecast audio is extracted (exploiting the BBCs 'listen again' function). This recording is shaped in real time by convolution with *Sailing By* which distorts and filters the original audio in an unpredictable way, bringing to mind an analogue radio tuning in and out. Slices of the forecast are played (between one and three seconds, enough to extract recognisable phrases from the forecast such as "moderate, good" or "rain later") and the sound itself 'tours' round the areas in the same order as the forecast would be read out (roughly clockwise from Viking) at a speed determined by the wind speeds reported for each area. The faster the wind, the quicker the sound moves through that area.

4.10.3 Evaluation

Squally Showers represents a niche in this portfolio as it is a sonification of data that is already, in a way, sonified when it is read on air by a BBC announcer. Indeed, a large part of the cultural resonance (see Carolan, 2011) of the shipping forecast is in its litany-like reading with its "solemn, rhythmic intonation" (Connelly, 2005, p 1.), especially the late-night broadcast. One may rightly ask, why try to improve it? My response is that my sonification 'collapses' the shipping forecast from a linear reading to one where the audience adopts an omnipresent position, immersed in every area of the forecast at once (a similar observation is made in relation to *The Beach Buoys* and *Notes from Underground*). A large part of this is down to the spatial dimension of the data. *Squally Showers* can be considered the 'largest' work in this portfolio with 30 sounding 'nodes' based on the shipping areas. In an installation context the ideal realisation of this work is for each node (area) to be heard on a single speaker, placed in a pattern based on the location of the shipping areas themselves. A listener in the centre of this speaker array facing 'north' would have sounds generated by the data from areas such as Hebrides and South Utsire in front of them, Dover and Wight behind them , Irish Sea and Shannon to their left and Tyne and German Bight to their right. The listener would be surrounded by the sounds of the waters around the UK. *Squally Showers* builds on elements already finessed throughout the portfolio – the use of sound materials that are strongly linked with the data source (in this case the theme song *Sailing By* as well as ships' bells and finally the data source itself being read out). However where other pieces have orientated themselves around one mapping (e.g. *The Beach Buoys* and *Singing in the Wires* having a single drone), *Squally Showers* attempts to develop several layers (by analogy it could be seen as an ensemble piece, if others are solos) which interact and work on the basis of different mappings. *Squally Showers* represents a point in the research where many of the methodological learnings taken from other pieces were incorporated to create an ambitious and large piece. In some instances the same data (e.g. windspeed) is subject to different mappings in the same sonification – it alters the 'organ stops' heard in the time-stretched drone, but also the speed in which forecast snippets flow round the areas.

5. Conclusion

5.1 Sonification as a means to generative music

I set out in this portfolio to explore whether sonification (defined as the transformation of non-musical data into sound) was a viable strategy for producing generative music (defined as music that was created in real time on a potentially infinite timescale). In each case, the selection of live data sources which are constantly changing in real-time has allowed me to create pieces that fulfil my definition of generative music and, from the point of view argued in my review of the literature, are works of sonification that are atypically focused on the sonification of live data, rather than the auditory display of existing fixed data. On this point I offer the portfolio of works as evidence of a successful exploration. In the first part of this concluding section I want to reflect on how the initial methodology outlined in chapter 3 was explored and refined throughout the creation of the portfolio.

I also set out to show that the mapping strategies adopted in the composition process were not simply arbitrary linkages between the properties of a sound (be it pitch, amplitude, timbre) and a fluctuating data but were artistically coherent choices made in response to, and in artistic engagement with, the underlying data. I also wanted to demonstrate that the soundworld created in each piece was coherently related to the data driving it as no matter how intricate the mapping scheme, the creative output is ultimately about the resulting soundworld and sounds heard. In the following two sections I will engage with these two points in more depth and with reference to works across the portfolio.

5.2 Working iteratively, refining and adapting my methodology

As outlined in section 1.6, one aim of pursuing this research was to discover whether a general methodology, or set of strategies for sonifying live data to create generative works could be discovered, then applied to a range of data sources to create a range of works. In chapter 3 I outlined the basic workings of this methodology – the discovery of a data source, the forming of a concept for the work then the iterative process of working with the properties of the data and the sounds they require, tuning the work as necessary to an artistic goal. This process is documented in relation to each work in chapter 4. In this section I want to set out how the methodology was adapted, improved and refined over the course of the portfolio and has led to some central findings.

The major breakthrough at the start of the portfolio was to alight on the idea that existing audio could be plundered not just for an important conceptual link to maintain coherency (either as musical puns, or anecdotally related to the data) but also as a soundworld that I found expressive of my own personal taste for slowly unfolding dronescapes. In particular I wanted to avoid the trap that some works of sonification fall into by aggressively mapping data (through scaling) onto pitch producing a series of random notes rendered in unrelated sound (often synthesised familiar instruments such as piano). Existing material, modified by time stretching and changes in the real-time source produced a soundworld that intrigued and motivated me and became something of a motif for the whole portfolio, but with each piece I attempted to explore the soundworld in a slightly different way, driven by the source data. Not all the pieces employed this dronescape aesthetic – if they were not appropriate to the data – in the case of *Currency Wars* for example, where I wanted the fast-paced skittering nature of the dataset to be reflected or *Protest Songs* where I wanted the reading aloud of individual petitions to be intelligible.

Over the course of the portfolio several tools or approaches for 'reading' the data were discovered and subsequently featured in the design of several works. Whilst maintaining that each work was a fresh exercise, in an evolutionary manner, successful ideas survived and became part of the toolkit, or armoury to be deployed later. I began the portfolio by simply looking for variables in the data that changed regularly enough to produce audible change at any one moment. The mapping of a variable heading in one direction or another produces the steady change in time heard in *Troy Ounce* and *Ephemeris de la Lune.* With later works I became more creative with the way I read the data – the breakthrough coming with *Singing in the Wires* and the reading of the national grid demand in gigawatts not as a number getting larger or smaller over time but as an instruction to sound a series of chords with changing intervals. This 'weird numerology' (see section 4.3.3) became part of my toolkit for finding my way through other datasets (it was re-employed in *Singing in the Wires* and *Squally Showers*) and I believe this constitutes an original way of thinking about numeric data in relation to artistic sonifications.

To demonstrate the accretion of techniques throughout the portfolio, the final piece, *Squally Showers,* can be seen to have incorporated all the methodological learning done throughout the entire portfolio. In some ways I regard it as the culmination of the many experiments on how to sonify data represented by earlier pieces in the portfolio. The use of existing audio conceptually related to the source data and its treatment via time stretching goes back to my earliest works (*Troy Ounce, Ephemeris de la Lune* and others) and the idea of many layers of time-stretched material heard in a filtered way goes back to *Ephermeris de la Lune* and *The Beach Buoys.* The nature of the time-stretching as a bank of 'organ stops' shows that original ideas can still be suggested by the data even when this 'signature sound' is employed. Although they are not quite manipulated in the same way (forming steps on an envelope curve, rather than harmonics) the idea of 'reading' numeric data as a musical mapping was formed as early as *Singing in the Wires* and *Singing Wikipedia.* Likewise the use of field recordings – anecdotal sound directly sourced or related to the data – was first experimented with in *Protest Songs* and refined in *Notes from Underground*. Although the idea resurfaces here, the idea of a radio tuning in and out is peculiar to this piece and directly related to the Shipping Forecast itself.

5.3 The underlying nature of the data: its influence on the artwork

Throughout this portfolio of works the underlying nature of the data being sonified has been a key driver of the structure of the resulting piece. Through a process of reflection on the nature of the data and how it may translate into a musical idea the compositions have come into being (this is outlined in the ‘genesis and influence’ sections for each piece in chapter 3). This compositional process has at all times been related back to my stated desire (section 1.6) to achieve artistic coherence between the data and resulting artwork. The compositional process is the practical relation of the theoretical discussion in sections 2.1.3, 2.1.4 and 2.1.5 where artistic schemes (second-order sonification) is balanced against accurately reflecting the underlying data (indexicality) and being 'true to the data'.

The most unifying aspect of all the datasets used throughout the portfolio is their 'liveness' (see discussion in section 1.6 and 2.3 in relation to works using fixed, non-live data). To satisfy the properties of generative music I have outlined in section 2.2, the datasets sonified in this portfolio have all been updated in real-time and are potentially infinitely flowing. Within this constraint each dataset has its own unique properties which influence the subsequent composition.

For example, the frequency of change in the data is a key driver of the resulting work’s ‘tempo’ (in a broad sense, rather than a metronome mark). The rapidly changing data from the currency exchange sonified in *Currency Wars* implies a rapid tempo, the slow progression of the moon through the sky over 24 hours implies a slower pace in *Ephemeris de la Lune*. To an extent the tempos are fixed by external factors such as how often an API is updated (so changes in *Singing in the Wire*s, for example, are influenced by the five minutes between data updates, or *In Flight Music* every 15 seconds, whereas *Currency Wars* is polled near continuously, the only limit being the computer’s speed in parsing and processing the data for sonification). However, this does not make the schemes arbitrary; on the contrary, the underlying nature of the data is incorporated into the compositional scheme as part of the creation of the work.

Other musical parameters such as the articulation of various pieces is influenced by the underlying nature of the data. *Currency Wars* features staccato ‘events’ (the change in each currency relationship), whereas *Singing in the Wires* features an unbroken drone (as the electricity grid is always 'on'). In between lies *In Flight Music* which is characterised by long tones which nevertheless have their entrances and exits based on the proximity of aeroplanes entering and exiting the ‘radar’ set around Sheffield (although this is a function of the selected – composed – parameters of that piece; a contrasting example recording demonstrates the piece with the co-ordinates set around Frankfurt, Germany where the presence of a large international airport – and therefore the constant presence of air traffic – results in a continuous sound, where the entrances and exits blur into one).

The flow of the data also influences the structuring of pieces in the portfolio. For example: in *Ephemeris de la Lune* the data is cyclical – a movement from 0 to 100% happening over 24 hours (in the case of the position of the moon in the sky) or 30 days (in the case of brightness). In *Currency Wars* the data implies a binary or oppositional relationship (the currency pair) where either one or the other advances; where one advances and is articulated the other retreats and is muted. In *Singing in the Wires* the data (the fundamental frequency of the grid and the drone) floats around an ideal 50Hz, in constant flux, whereas in *Protest Songs* the data is linear (each petition garners more and more signatures; it can't 'go backwards') but each signature is treated as a discrete event, either causing the petition to be voiced or not.

At another level the source of the data can influence the structure of a piece (a manifestation of being 'true to the data' discussed in section 2.1.5) – there is only one National Grid, for example, so there is one unified drone sounding in *Singing in the Wires*. In *Currency Wars* there are eight major currencies, so a coherent (as I have sought to define it) presentation takes these eight into account, translating into eight voices and eight channels. For *Notes from Underground* or *In Flight Music* an arbitrary number of voices – the number of trains approaching a selected stop, the number of aeroplanes in the air – need to be heard. To me this suggested each train or aeroplane should be a unique 'atom' of sound in the piece, with their aggregate making up the piece in that moment. Indeed, a challenge with the composition of *Squally Showers* was the unwieldy incorporation of all the shipping forecast areas the subsequent mass of sound produced – this implied a vast multi-channel presentation that allowed each sound to be heard.

My research question does not ask whether any of these compositional, sonification decisions are 'correct' (the implication being that in a scientific sense for any given dataset there is an idealised sonification to be discovered), but rather such compositional choices 'make sense' and are coherent within the context of the artwork. The answers to such questions are sometimes simple. For example, the spatial location of an aeroplane in *In Flight Music* east-west is rendered left-right in a stereo field[1]. It would be frankly odd if an increase in the frequency of the National Grid in the data did not result in an corresponding increase in the frequency of the pitch of the drone of *Singing in the Wires.* Other compositional decisions such as creating an analogy between the cyclical passage of the moon and the position in a sound file, as I tried to describe it, 'like a giant record played by a cosmic needle' (*Ephemeris de la Lune)* require more artistic licence, although I found them no less coherent for this (I feel, ultimately my artistic decisions are justified and made not arbitrarily but in response to the underlying nature of the data). But coherency is not absolute: a different artist may arrive at different yet equally coherent artistic decisions (see Stockhausen quoted in the conclusion of section 2.1.4).

5.4 Coherency in the soundworld

Perhaps more important than the underlying structure of the piece is the soundworld it creates. It is in the conception and creation of this soundworld that I have also attempted to explore the idea of coherency. As described in the creation of each piece (section 3), as a set of data is being considered for sonification

1 This was a concession to the stereo rendering of the piece, a more comprehensive multi-channel presentation could spatialise based on north-south too.

there comes a point when the soundworld must also be conceived. To achieve artistic coherency between my chosen data and the sounds heard I have taken the view that each project must be a bespoke enterprise [2] considering carefully the nature of the data and how to 'give it a voice'. As I explored my initial ideas in making each work in the portfolio, the process of giving the data voice emerged as the key challenge for my research, a problem to be solved.

One approach was to construct soundworlds around musical puns where an artistic link was drawn between an existing sound source and the data being sonified (an example of the 'troping' identified by Brubaker (2009) (see section 4.2.1) or ReMapping 'second-order' sonification practice espoused by Gresham-Lancaster and Sinclair (2012) (see section 2.1.2) . Thus, Spandau Ballet's *Gold!* was chosen as a source for *Troy Ounce,* the *Moonlight Sonata* for *Ephemeris de la Lune,* a small sample of the Beach Boys for *The Beach Buoys,* national anthems in *Currency Wars* and *Sailing By* in *Squally Showers.* In most cases these source sounds are not readily identifiable given their transformation (time stretching and layering of multiple versions in the case of *Troy Ounce, Ephemeris de la Lune* and *Squally Showers,* filtering and time-stretching in *The Beach Buoys* an taking very small sections of sound in *Currency Wars*). It is my intention that the 'punning' link between sound and data sets up the artistic coherency (the choice of source material is not arbitrary but conceptually linked to the underlying data being sonified). In the previous section I have written about compositional choices feeling like they 'make sense' – the pieces in the portfolio that rely on a conceptual pun would be absurd if there wasn't some link. Although the structural idea behind *Troy Ounce* – the idea that moving gold prices are driving four virtual records back and forth – would work with *any* sound source, and arguably produce a broadly similar sonic effect (a slowly shifting soundworld characterised by the blurred windows of FFT time-stretching), to me it would not be artistically coherent (nor conceptually defensible) if the sound source were simply a randomly chosen piece of music. That is not to say that other similarly punning sound sources could not be alighted on to make a different sounding piece (*Money* by Pink Floyd, or *Money, Money, Money* by Abba spring to mind) even if the underlying structure were the same. An open question remains: if the associated sound source is so important, but is completely abstracted by the sound processing applied to it, how is the audience to be made aware of the conceptual basis of the work? Composers are used to producing performance notes in concert programmes and exhibitions often have accompanying text which 'explain' or contextualise and artwork. Is this necessary or even desirable in the case of sonifications?

Another approach was to construct the sound from the data itself (at least in part). In *Singing Wikipedia* the sound (the computer voice reading the random Wikipedia article) comes wholly from Wikipedia itself; no external musical source is used. The data which transforms it (creating a chord) is also drawn from the Wikipedia API. Likewise in *Protest Songs* the voice layer is drawn directly from the data on the government petitions website. Artistic coherency is maintained by making the soundworld and the data

2 I have rejected the approach where a 'universal sonification engine' can be made, although such tools are available e.g. SoniPy – see https://www.physense.eu/sonification-projects-and-software/). Views on the appropriateness of this approach are perhaps a manifestation of the scientific/artistic schism described in section 2.1.4

one and the same, although it may be argued that the transformations required to produce a musical result make for a contrived coherency.

Along similar lines, it is possible to make the soundworld directly linked to the subject of the data. A layer of *Protest Songs* is based on the perturbation (Gresham-Lancaster's phrase) of sound recordings of actual protests and *Notes from Underground* uses the sounds of actual underground stations and trains triggered by data from the London Underground. The link between data and soundworld in these cases is perhaps undeniable, however the problem remains of how the link between the two is signalled to the audience. Listeners may quickly catch on to the origin of the source sound (especially in *Protest Songs* where they are untransformed) but why they are changing in time is still opaque.

There are two pieces where the soundworld is more tenuously linked to the underlying data. In *Singing in the Wires* a drone is constructed from a bowed guitar string, rich in harmonics. The coherency comes from the link with the buzzing wires of high voltage. In *In Flight Music* the sound is of a vintage electronic organ – again a richly harmonic drone. This is a coherent choice in relation to aeroplanes in that they also make long continuous sounds where a soundworld based on highly rhythmical materials (a salsa beat changing in tempo, say) would be out of place, or at least hard to defend conceptually.

5.5 Final thoughts

The goal of generative music is to create soundworlds which are continuous and continuously changing, never repeating in the exact same combination. The exploration of data sonification to provide the basis for such constant change has been a fruitful one for me, spawning the works presented here. The challenge for myself as a composer has not been so much in the manipulation of data (although significant effort has gone into the discovery of open sources of data and the requisite 'data wrangling' allowing it to be sonified) but in coming up with mapping schemes that relate coherently to the data source and a soundworld that is personally stimulating as a creative project. This is where the composition process and creative act reside.

The presentation of generative works remains a subject for further study. The infinite nature of generative pieces does not lend itself, and indeed seeks to break with, traditional concert or fixed media presentation[3]. Installations, where sound plays for as long as a space is open and the audience are free to experience as much or as little of a piece as they choose are one avenue, as explored by John Luther Adams in *The Place Where You Go to Listen* (2009) among others. As the originator of the term generative music, Brian Eno has argued (Baccigaluppi & Crane, 2011; Jacques, 2019) that the birth of the smartphone (seen as

3 David Grubbs has written compellingly about the problems faced by experimental artists with the amenability of their work to traditional forms of presentation in *Records Ruin the Landscape* (2014). Although the focus of his research is the experimental tradition in the post-war avant garde rather than contemporary sound art practice.

a portable computer and hi-fi audio device) heralds the ideal platform for his generative ideas which were once cumbersome, requiring proprietary software and hardware. However, the adoption of generative music (generated by the sonification of data or otherwise) envisioned by Eno in the mid 1990s (Eno, 1996a, p. 332) has yet to reach the everyday popularity of concert-going or listening to LPs, CDs or streaming durational music, and therefore remains fertile ground for future work and exploration.

References

About the Journal of Henry David Thoreau (n.d.). Retrieved from https://www.penguinrandomhouse.com/books/178472/the-journal-of-henry-david-thoreau-1837-1861-by-henry-david-thoreau/9781590173213/

Adams, J. L. (2009), *The Place Where You Go to Listen: In Search of an Ecology of Music*, Middletown, Connecticut : Wesleyan University Press

Baccigaluppi, J & Crane, L. (2011), Brian Eno: U2, Coldplay, Talking Heads, *Tape Op Magazine,* #85 September-October 2011. Retrieved from https://tapeop.com/interviews/85/brian-eno/

Barrass, S and Vickers, P. (2011), Sonification Design and Aesthetics, in Hermann, T., Hunt, A., Neuhoff, J. G., (eds) *The Sonification Handbook* (pp. 145-171). Berlin: Logos Publishing House

Bianksteen, J. (1979), Computer Synthesizes 'Music of the Spheres', New York Times, 24th April 1979. Retrieved from http://www.nytimes.com/1979/04/24/archives/computer-synthesizes-music-of-the-spheres-music-of-spheres.html?_r=1

Boden, M. A. and Edmonds, E. A. (2010), What is generative art?, *Digital Creativity*, *20*(1-2), 21-46

Brubaker, B. (2009), Time is time: temporal signification in music in Crispin, D. (ed) *Unfolding Time Studies in Temporality in Twentieth Century Music* (pp. 95-118), Leuven: Leuven University Press

Cage, J. (1961) *Silence: Lectures and writings*. London: Marion Boyars

Cage, J. (1963), *A Year From Monday.* Middletown, Connecticut: Wesleyan University Press:

Cage, J. (1981), *Empty Words: Writing 73-78,* London: Marion Boyars

de Campo, A. (2007), Toward a data sonification design space map, P*roceedings of the International Conference on Auditory Display (ICAD)*, Montreal, Canada. Retrieved from http://www.interactive-sonification.org/ISon2007/proceedings/papers/deCampo_ISon2007.pdf

Carl, R. (2009), *Terry Riley's In C,* Oxford: Oxford University Press

Carl, R. (2012) Place and Space: The Vision of John Luther Adams in the Ultramodern Tradition in Herzogenrath, B. (ed). *The Farthest Place: The Music of John Luther Adams* (pp. 206-218), Boston: North Eastern University Press

CDIP (n.d.), [website of the Coastal Data Information Program] Retrieved from https://cdip.ucsd.edu/

Clayton, J. (2010, November), The Slowed-Down Tempos of Screw and its Influence on Contemporary Bands, *Frieze Magazine.* Retrieved from https://frieze.com/article/music-6

Cohen, J. (1994), Monitoring Background Activities in Kramer, G. (ed) *Auditory Display: Sonification,* *Audification and Auditory Interfaces* (pp. 499–531). Reading, Mass: Addison Wesley.

Collins, N, (2002) Infinite Length Pieces: A User's Guide. Retrieved from https://community.dur.ac.uk/nick.collins/research/infinite.pdf

Collins, N. (2008), The Analysis of Generative Music Programs, *Organised Sound, 13*(3), 237-248.

Collins, N. (2009), Musical Form and Algorithmic Composition, *Contemporary Music Review, 28*(1), 103-114.

Collins, N and Brown A. R. (2009), Generative Music Editorial, *Contemporary Music Review, 28*(1), 1-4.

Connelly, C. (2006), *Attention All Shipping: A Journey Round the Shipping Forecast,* London: Abacus

Cope, D. (2009) in Artists' Statements, *Contemporary Music Review, 28*(1), 124-125

Cross, L. (1999). Reunion: John Cage, Marcel Duchamp, Electronic Music and Chess, *Leonardo Music Journal*, 9, 35-42.

Croft, J. (2005), Composition is not research. *Tempo, 69*: 6-11

Cutler, C. (2004) Plunderphonia in Cox, C. and Warner, D. (eds), *Audio Culture: readings in modern music* (pp. 138-156). London: Continuum

Dombois, F. & Eckel, G. (2011). Audification in Hermann, T., Hunt, A. & Neuhoff, J. G. (eds), *The Sonification Handbook* (pp 301–324). Berlin: Logos Publishing House

Dorin, A. Generative processes and the electronic arts, *Organised Sound*, *16*(1) 47-53.

Dorin, A., McCabe J. , McCormack, J., Monro, G. & Whitelaw, M. (2012), A framework for understanding generative art, *Digital Creativity*, 23:3-4, 239-259

Doornbusch, P. (2005), Pre-composition and Algorithmic Composition: Reflections on Disappearing Lines in the Sand, *Journal of Music Research, 29*(30), 47-58.

Doornbusch, P. (2009), Early hardware and early ideas in computer music - their development and their current forms in Dean, R.T. (ed) *The Oxford Handbook of Computer Music* (pp. 44-84). Oxford: Oxford University Press

Duckworth, W. (2005), *Virtual Music: How the Web Got Wired for Sound*, London: Routledge

Eacott, J. (2007), “Contents may vary: the play and behaviour of generative music artefacts” (PhD Thesis, University of Westminster)

Eacott, J. (2009), in Artists' Statements, *Contemporary Music Review, 28*(1), 115-128

Eacott, J (2011), Flood Tide See Further: Sonification As Musical Performance, In: *Proceedings of the International Computer Music Conference 2011*, University of Huddersfield, UK, 31 July - 5 August 2011. Retrieved from http://quod.lib.umich.edu/cgi/p/pod/dod-idx/flood-tide-see-further-sonification-as-musical-performance.pdf?c=icmc;idno=bbp2372.2011.013

Eacott, J. (2012a), Instant music? Just add water, *AI & Society, 27*(2), 287–288.

Eacott, J. (2012b), Flood Tide: sonification as musical performance—an audience perspective, *AI & Society, 27*(2), 189–195.

Eacott, J. (2013), *Floodtide the next 5 years.* [blog post]. Retrieved from http://www.floodtide.eu/posts/floodtide-the-next-5-years

Eigenfeldt, A. (2016, September) Exploring Moment Form in Generative Music presented at Sound and Music Computing, Hamburg, Germany. Retrieved from https://www.researchgate.net/publication/306207035_EXPLORING_MOMENT-FORM_IN_GENERATIVE_MUSIC

Eno, B. (1994), Resonant Complexity, *Whole Earth Review,* Summer 1994. Retrieved from https://www.moredarkthanshark.org/eno_int_wer-sum94.html

Eno, B. (1996a), *A Year With Swollen Appendices,* London: Faber

Eno, B. (1996b), Generative Music, A talk delivered in San Francisco, June 8, 1996, *In Motion Magazine*. Retrieved from http://www.inmotionmagazine.com/eno1.html

Eno, B. (2017), *Brian Eno on Reflection* [online liner notes to album]. Retrieved from https://brian-eno.net/reflection/index.html

Essl, K. (2007), Algorithmic composition in Collins, N and d'Escrivan, J (eds), *The Cambridge Companion to Electronic Music* (pp. 107-215). Cambridge: Cambridge University Press

Foster, C. D. (1995), A Consonance Dissonance Algorithm for Intervals in *Proceedings of the International Computer Music Conference 1995,* Banff, Canada, September 3-7 1995 (pp. 587-588). Retrieved from https://quod.lib.umich.edu/i/icmc/bbp2372.1995?rgn=full+text

Floodtide: Listening Post. (2014, April 3). retrieved from https://www.timeout.com/london/things-to-do/floodtide-listening-post

Freesound.org (n.d) [online sound resource]. Retrieved from https://freesound.org/

Grubbs, D. (2014), *Records Ruin the Landscape: John Cage, the Sixties and Sound Recording,* Durham and London: Duke University Press

Hansen, M. and Rubin, B. (2002) Listening Post: Giving Voice To Online Communication in *Proceedings of the 2002 International Conference on Auditory Display, Kyoto, Japan, July 2-5, 2002.* Retrieved from https://www.researchgate.net/publication/2839828/download

Harley, J. (2011), Computational Approaches to Composition of Notated Instrumental Music: Xenakis and the Other Pioneers in Dean, R. T. (ed), *The Oxford Handbook of Computer Music,* Oxford: Oxford

University Press

Harper, A. (2011), *Infinite Music*, Winchester: Zero Books

Harris, Y. (2011), Scorescapes: on sound, environment and sonic consciousness (PhD Thesis, Leiden University) Retrieved from https://openaccess.leidenuniv.nl/handle/1887/18184

Herzogenrath, B. (2009), The "weather of music" : sounding nature in the twentieth and twenty-first centuries in Herzogenrath, B. (ed.) *Deleuze/Guattari & Ecology* (pp. 217-232). Basingstoke: Palgrave-Macmillan

Hermann, T (2008), Taxonomy And Definitions For Sonification And Auditory Display, *Proceedings of the 14th International Conference on Auditory Display*, Paris, France June 24 - 27, 2008. Retrieved from http://www.icad.org/Proceedings/2008/Hermann2008.pdf

Hermann, T (2010), Sonification: A Definition. Retrieved from http://sonification.de/son/definition

Hermann, T. (2011), Model-based sonification, in Hermann, T., Hunt, A. & Neuhoff, J. G. (eds), *The Sonification Handbook* (pp. 399–427). Berlin: Logos Publishing House

Gann, K. (2006), Fairbanks: A Long Ride in a Slow Machine, *New Music Box* 29/3/2006. Retrieved from http://www.newmusicbox.org/articles/fairbanks-a-long-ride-in-a-slow-machine/

Gann, K. (2010), *No Such Thing as Silence: John Cage's 4' 33"*, New Haven: Yale University Press

Gresham-Lancaster, S. (2012), Relationships of sonification to music and sound art, *AI & Society, 27*(2), 207–212.

Gresham-Lancaster, S. and Sinclair P. (2012), Sonification and Acoustic Environments, *Leonardo Music Journal*, 22 67-71.

Gridwatch (n.d.) [website monitoring national grid] https://www.gridwatch.templar.co.uk/

Jaques, J. (April 1st, 2019) Suite 212 - 1st April 2019 Brian Eno [audio podcast]. Retrieved from https://www.mixcloud.com/Resonance/suite-212-1st-april-2019-brian-eno/

Jefferson, P. (2011), *And Now The Shipping Forecast: A Tide of History Around Our Shores,* Cambridge: UIT

Johnstone, R. (2013), Creating a coral symphony: sound art and sonification*, Etropic: electronic journal of studies in the tropics*, 12:2 191-196.

Jones, S. (2012) , Sonification: the element of surprise, *AI & Society, 27*(2), 297–298.

Kramer, G. (1994), An Introduction to Auditory Display, in Kramer, G. (ed) *Auditory Display: Sonificaiton, Audification and Auditory Interfaces*, (pp. 1–78). Reading, Mass: Addison Wesley.

Kramer, G., Walker, B., Bonebright, T., Cook, P., Flowers J. H., Miner, N. & Neuhoff, J. (1999), *Sonification Report: Status of the Field and Research Agenda Prepared for the National Science Foundation by members* *of the International Community for Auditory Display* [White paper]. Retrieved from http://sonify.psych.gatech.edu/publications/pdfs/1999-NSF-Report.pdf

Kreidler, J (2009), Programming Electronic Music in Pd [online programming resource]. Retrieved from http://pd-tutorial.com/english/ch03s08.html

Landy, L. (1994), The "something to hold on to factor" in timbral composition, *Contemporary Music Review, 10*(2), 49-60.

McKinney, C. & Renaud, A. (2011, July), Leech: Bittorrent And Music Piracy Sonification, Paper presented at Sound and Music Computing Conference, Padova, Italy. Retrieved from http://smc.afim-asso.org/smc11/papers/smc2011_154.pdf

Miranda, E. R. (2009), Preface: Aesthetic Decisions in Computer-Aided Composition, *Contemporary Music Review 28*(2), 129-132.

Modes, W. (2014), Listening Post Ten Years On, *NmediaC: The Journal of New Media and Culture* 9:1. Retrieved from http://modes.io/listening-post-ten-years-on/

Neirhaus, G. (2009), *Algorithmic Composition: Paradigms of Automated Music Generation,* Springer: Vienna.

Niblock, P. (2007), Biography [personal website]. Retrieved from https://phillniblock.com/2007/06/14/biography-photos/

OpenSky Network (n.d.) [website] https://opensky-network.org/about-heading/about

Parkinson A. and Tanaka A. (2014), Making Data Sing: Embodied Approaches to Sonification. in Aramaki M., Derrien O., Kronland-Martinet R., Ystad S. (eds) *Sound, Music, and Motion. CMMR 2013. Lecture Notes in Computer Science* (pp. 151-160). Cham, CH: Springer

Parviainen, T. (2017). Terry Riley's "In C" A Journey Through a Musical Possibility Space [online blog post]. Retrieved from http://teropa.info/blog/2017/01/23/terry-rileys-in-c.html

Palmer (nee Reiser), M. and Jones, O. (2011) On breathing and geography: Sonifying the Severn as shared generative art practice. In:*ISEA2011 Istanbul, The 17th International Symposium on Electronic Art*, Istanbul, Turkey, 14th - 21th September, 2011. Istanbul, Turkey: Sabanci University. Retrieved from http://eprints.uwe.ac.uk/20633

petition.parliament.uk, (n.d). [webpage for petitions to parliament]. Retrieved from https://petition.parliament.uk/

Polansky, Larry. (2002). Manifestation and Sonification: The Science and Art of Sonification, Tufte's Visualization, and the "slippery slope" to Algorithmic Composition (An Informal Response to Ed Childs' Short Paper on Tufte and Sonification). Retrieved from http://eamusic.dartmouth.edu/~larry/sonification.html

Polli, A. (2006), Heat and the Heartbeat of the City: Sonifying Data Describing Climate Change, *Leonardo Music Journal*, *16*, 44-45.

Polli, A. (2012), Soundscape, sonification, and sound activism, *AI & Society, 27*(2), 257–268.

Pritchett, J. (1993), *The Music of John Cage,* Cambridge: Cambridge University Press

Randerson, J. D. (2013). Cloud Music: a cloud system in Cleland, K., Fisher, L. & Harley, R. (Eds.) *Proceedings of the 19th International Symposium of Electronic Art*, ISEA2013, Sydney, Australia 7-16th June 2013. Retrieved from https://ses.library.usyd.edu.au/bitstream/2123/9684/1/cloudmusic.pdf

Radovic, S. (2008, 9th December), *First computer to sing - Daisy Bell* [youtube video]. Retrieved from https://www.youtube.com/watch?v=41U78QP8nBk

Reich, S. (1968), Music as a Gradual Process in Reich, S. (2002), *Writings On Music* (pp. 34-26). Oxford: Oxford University Press

Reynolds, S. (1994), The Ambient Rock Pool, *The Wire,* Issue 123 May 1994, 28-33

Richards, C. (2011, 30 December), A 44-minute disc that takes 4 months to play? It's time stretching, *The Washington Post.* Retrieved from https://www.washingtonpost.com/lifestyle/style/time-stretching-warps-songs-into-sprawling-blurs/2011/12/27/gIQASnwARP_story.html?noredirect=on&utm_term=.9aef58c4a267

Riley, T. (1964), In C Performance Directions [musical score directions]. Retrieved from https://www.datenbankneuemusik.de/fileadmin/user_upload/datenbank/werke/i/VORSCHAU_In_C_Riley_Instructions.pdf

Roads, C. (2001), *Microsound*, Cambridge, Mass: MIT Press

Roads, C. (2006), *The Computer Music Tutorial*, Cambridge, Mass: MIT Press

Roads, C. (2015), *Composing Electronic Music*, Oxford: Oxford University Press

Rodgers, J. and Ruff, W. (1979), Kepler's Harmony of the World: A Realization for the Ear: Three and a half centuries after their conception, Kepler's data plotting the harmonic movement of the planets have been realized in sound with the help of modern astronomical knowledge and a computer-sound synthesizer, *American Scientist, 67*(3) 286-292.

Ross, A. (2010), *Listen to This,* London: Fourth Estate

Rothenburg (2012), How Music Based on Nature Might Not Need Natural Sounds in Herzogenrath, B. (ed) , *The Farthest Place: The Music of John Luther Adams* (pp.107-115). Boston: Northeastern University Press

Rutherford-Johnson, T. (2017), *Music After the Fall,* Oakland: University of California Press

Rutherford-Johnson, T., Kennedy, M. and Kennedy J. B. (eds) (2013) *The Oxford Dictionary of Music* (6 ed.), Oxford: Oxford University Press

Scaletti, C. (1994), Sound Synthesis Methods for Auditory Data Representation, in Kramer, G. (ed) *Auditory Display: Sonification, Audification and Auditory Interface* (pp. 223-251). Reading, Mass: Addison Wesley.

Scaletti, C. (2018), Sonification ≠ Music in Dean, R. T. & McLean, A (eds) *The Oxford Handbook of Algorithmic Music* (pp.364-385). Oxford: Oxford University Press.

Schaefer J. (2001), AudiOh!!: Appropriation, Accident and Alteration, *Leonardo Music Journal, 11* 71-76

Schedel, M. & Worrall, D. (2014), Editorial. *Organised Sound*, *19*(1), 1-3.

Schoon, A. and Dombois, F. (2009) Sonification in music. *Proceedings of the 15th international conference on auditory display,* Copenhagen, Denmark, 18-22 May. Retrieved from http://www.dev.icad.org/Proceedings/2009/SchoonDombois2009.pdf

Serra, M-H. (1993), Stochastic Composition and Stochastic Timbre: GENDY3 by Iannis Xenakis, *Perspectives of New Music*, *31*(1), 236-257.

Smithsonian, Cloud Music (n.d.) [website catalogue of works]. Retrieved from https://www.si.edu/tbma/saam_cloudmusic

Spiegel, L. (2009) in Artists' Statements, *Contemporary Music Review, 28*(1), 127-128

Sterne, J. and Akiyama, M., The Recording That Never Wanted to Be Heard and Other Stories of Sonification in in Pinch, T. and Bijsterveld, K. (eds) *The Oxford Handbook of Sound Studies,* Oxford: Oxford University Press

Supper, A. (2012), The Search for the “Killer Application”: Drawing the Boundaries around the Sonification of Scientific Data, in Pinch, T and Bijsterveld, K (eds), *The Oxford Handbook of Sound Studies* (pp. 284-270), Oxford: Oxford University Press

Supper, A. (2014), Sublime frequencies: The construction of sublime listening experiences in the sonification of scientific data. *Social Studies of Science, 44*(1) 34–58

Sturm, B. L. (2005), Pulse of an Ocean: Sonification of Ocean Buoy Data, *Leonardo, 38*(2), 143-149.

Tingen, P. (2005), Brian Eno: Recording Another Day On Earth, *Sound on Sound,* October 2005 https://www.soundonsound.com/people/brian-eno

Toop, D. (2004), *Haunted Weather: music, silence and memory,* London: Serpent's Tail.

Tuck, L. (1981), Utter 'Nonsense' From John Cage and Thoreau*, Washington Post* 30/9/1981. Retrieved from https://www.washingtonpost.com/archive/lifestyle/1981/09/30/utter-nonsense-from-john-cage-and-thoreau/19e53a9c-30b5-492e-ba8e-f7d5f9d184a5/?noredirect=on&utm_term=.99ffaf009603

Transport for London Unified API (n.d.). Retrieved from https://api.tfl.gov.uk/

UbuWeb (n.d.) [website archive of the avant garde]. Retrieved from http://www.ubu.com/

Van Ransbeeck, S. (2018), Sonification in an Artistic Context, Cermak-Sassenrath, D. (ed), *Playful*

Disruption of Digital Media (pp. 151-166), Singapore: Springer

Van Ransbeeck, S. (2017, June 26th), Conductor: the sound of the New York subway [Blog post]. Retrieved from https://sonificationart.wordpress.com/2017/06/26/conductor-the-sound-of-the-new-york-subway/

Vickers, P. & Alty, J. (2006), The Well-Tempered Compiler: The Aesthetics of Program Auralization in Fishwick, P. A. (ed), *Aesthetic Computing* (pp. 335-354). Cambridge, Mass: MIT Press

Vickers, P. (2016), Sonification and Music, Music and Sonification in, Cobussen, M., Meelberg, V., Truax B. (eds), *The Routledge Companion to Sounding Art* (pp. 135-144). London: Routledge

Watts, R., Behrman, D. & Diamond, B. (1992) Cloud Music, in Dunn, D. (ed.), *Eigenwelt der Apparatewelt, Pioneers of Electronic Art* (pp. 152-154). Retrieved from http://www.vasulka.org/Kitchen/PDF_Eigenwelt/pdf/152-154.pdf

Walker, B. N. and Lane, D. M. (2001) Psychophysical Scaling Of Sonification Mappings: A Comparision Of Visually Impaired And Sighted Listeners in *Proceedings of the 2001 International Conference on Auditory Display, Espoo, Finland, July 29-August 1, 2001* http://sonify.psych.gatech.edu/publications/pdfs/2001ICAD-WalkerLane-Paper.pdf

Walker, B. N. and Nees, M. A. (2011). Theory of sonification, in Hermann, T., Hunt, A. & Neuhoff, J. G. (eds), *The Sonification Handbook* (pp. 9–39). Berlin: Logos Publishing House

Williams, R. (1996), The Brain of Brian: interview with Brian Eno, *The Guardian* 10/5/1996. Retrieved from http://www.eno-web.co.uk/interviews/guard96a.html

Whitelaw, M. (2004), Hearing Pure Data: Aesthetics and Ideals of Data-Sound in *Unsorted : thoughts on the information arts: an A to Z for SonicActsX* (pp. 45-53). Amsterdam: Sonic Acts Press

Wooller, R., Brown, A., Miranda, E., Berry, R., & Diederich, J. (2005). A framework for comparison of process in algorithmic music systems. Presented at the Generative Arts Practice, Sydney, Australia, 2005. Retrieved from http://eprints.qut.edu.au/6544/1/6544.pdf

Worrall, D. (2009), An Introduction to Data Sonification, in: Dean, T ed. *The Oxford Companion of Computer Music* (pp. 135-144). Oxford: Oxford University Press

Wray, D. D. (2016), Art scientific: a world exclusive interview with Brian Eno, *Loud and Quiet* [online magazine] https://www.loudandquiet.com/interview/brian-eno-a-world-exclusive-interview/

Xenakis, I. (1992), *Formalized Music: 2nd Edition,* Stuyvesant, NY: Pendragon Press

Zbikowski, L M. (2002), *Conceptualizing Music: Cognitive Structure, Theory, and Analysis*, Oxford: Oxford University Press

Zuckerman, G. (2002), An Interview with La Monte Young and Marian Zazeela. Retrieved from: http://musicmavericks.publicradio.org/features/interview_young.html

Musical and other artworks cited

Adams, J. L. (2009), *The Place Where You Go to Listen* [sound and light installation], Fairbanks, Alaksa: The Museum of the North.

Baxter, I. (2013), *Playing the Weather* [sound installation], Birmingham Network Festival, [online description] http://www.ianbaxter.net/installations_ptwnmf.shtml

The Beach Boys (1966), You Still Believe in Me on *Pet Sounds* [CD] Los Angeles: Capitol Records

Cage, J. (1951), *Music of Changes*, London: Peters Edition EP 6256, EP 6257, EP 6258, EP 6259 (4 volumes)

Cage, J. (1952), *Williams Mix* [magnetic tape], London: Peters Edition EP 6774R

Cage, J. (1952), *Music for Piano*, London: Peters Edition EP 6729

Cage, J. (1968), *Reunion* [event for two performers playing a game of chess on a specially constructed electronic chess board] [online description]. Retrieved from http://johncage.org/pp/John-Cage-Work-Detail.cfm?work_ID=325

Cage, J. (1969), *HPSCHD*, London: Peters Edition EP 6804

Cage, J. (1970), *Song Books,* London: *Peters Edition EP 6806A*

Cage, J. (1974), *Empty Words*

Cage, J. (1975), *Etudes Australes,* London: Peters Edition EP6816a/b (books 1 & 2), EP6816a/d (books 3 & 4)

Cage, J. (1976), *Song Derived from the Journals of Henry David Thoreau,* http://www.ubu.com/sound/cage.html

Cage, J. (1981), *Etudes Borealis,* London: Peters Edition EP 66327

Chen, A. (2017), *Conductor: the sound of the New York subway* [online description][video] retrieved from https://sonificationart.wordpress.com/2017/06/26/conductor-the-sound-of-the-new-york-subway/

Dukich, T. (2004), *Can you hear me now? Sonified Weather: Spokane & Seattle* [self released CDr]. see http://www.tomdukich.com/weather%20songs.html

Eacott, J. (2008), *Floodtide* [generative music system for mixed ensemble] [online description] Retrieved from http://www.informal.org/documents/FloodTide%20specification%20Nov08.pdf

Eno, B, (1975), *Discrete Music* [LP] London: Obscure/Island Records Obscure no. 3

Eno, B, (1978), *Ambient 1: Music for Airports* [LP], London: Polydor/EG AMB 001

Eno, B. (2008), *Bloom* [Mobile application software]

Eno, B. (2012), *Scape* [Mobile application software]

Eno, B. (2017), *Reflection* [CD], London: Warp Records WARP280

Eno, B. (2017), *Reflection* [Mobile application software]

Feldman, M. (1983), *Crippled Symmetry,* London: Universal Edition UE 17 667

Ferrari, L. (1967-1970), *Presque Rein*

Ferrari, L. (1985), *Strathoven*

Finer, J. (2000), *Longplayer* [sound installation] London: Trinity Buoy Wharf

Foo, B. (2015), Two Trains: Sonification of Income Inequality on the NYC Subway, Retrieved from: https://datadrivendj.com/tracks/subway/

Gibson, J. (1977), *Two Solo Pieces* [LP] New York: Chatham Square Productions LP 24

Inge, L. (2004), 9 *Beet Stretch* [sound installation][online description and realisation]. Retrieved from http://www.xn--lyf-yla.com/

Juxtavoices (2015), *Guardian Weekend Remix,* Sheffield: Discus 54CD

Kubrick, S. (Producer & Director) (1968) , *2001: A Space Odyssey,* [motion picture] United States: MGM

Ligeti, G. (1961), *Atmosphères,* Vienna: Universal Edition

Ligeti, G. (1962), *Poeme Symphonique,* Mainz: Schott

Ligeti, G. (1966), *Lux Aterna,* London: Edition Peters EP5934

Lucier, A. (1965), *Music for Solo Performer, for enormously amplified brain waves and percussion*

Niblock, P. (2009), *Touch Strings* [CD], London: Touch TO79

Parviainen, T. (2017), *Real-time sonification of the Helsinki tram system,* [online sonification]. Retrieved from https://codepen.io/teropa/details/mBbPEe

Patterson, K. (2007), *Earth-Moon-Earth* [sound installation for automated grand piano] [online description]. Retrieved from http://katiepaterson.org/portfolio/earth-moon-earth/

Quinn, M. (2005), *Seismic Sonata, Music of the Earth, Sun, Planets & Space Volume One* [CD] Lee: New Hampshire Design Rhythmics Sonification Research Lab

Radiohead (1997), Fitter Happier on *OK Computer* [CD], London: Parlophone 7243 8 55229 2 5

Riley, T (1964). *In C,* New York: Associated Music Publishers

Saladin, M. (2007), *Stock Market Piece,* [online description] Retrieved from http://www.mattin.org/recordings/Matthieu_Saladin.html

Schaefer, J. (1997), *Tri Phonic Turntable* [modified record player] [online description]. Retrieved from http://www.audioh.com/projects/triphonic.html

Schaefer, J. (2007), *Extended Play,* [sound installation] [online description]. Retrieved from http://www.audioh.com/projects/extendedplay.html

Stockhausen, K. (1967), *Hymnen,* Kürten: Stockhausen-Verlag

Stone, C. (1986), Shing Kee on *Electronic Music from the Seventies and Eighties* [digital album] new York: Unseen Worlds, UW15

Sturm, B. (2003), *Pacific Pulse,* [online description] http://rhizome.org/art/artbase/artwork/pacific-pulse-electroacoustic-composition-for-8-channels/

Skempton, H. (1972), *Lament for Organ,* played by Carson Cooman [online video] https://www.youtube.com/watch?v=M9oa5mgLyJs

Tenney, J. (1961), *Collage #1 (Blue Suede)*, *Selected Works 1961-1969,* Artifact Recordings / ART 1007

Van Ransbeeck, S. (2019) Outros Registros: the sound and silence of police violence in Rio de Janeiro [installation][online description] retrieved from https://sonificationart.wordpress.com/2019/03/18/outros-registros-the-sound-and-silence-of-police-violence-in-rio-de-janeiro/

Watts, R., Behrman, D. & Diamond, B. (1974-1979) *Cloud Music* [sound and video installation] Washington DC: The Smithsonian Archive. Retrieved from https://www.si.edu/tbma/saam_cloudmusic see also video of Cloud Music, Retrieved from https://vimeo.com/51240280

Xenakis, I. (1955), *Metastasis*, London: Boosey & Hawkes

Xenakis, I, (1956), *Pithoprakta,* London: Boosey & Hawkes

Xenakis, I. (1959), *Duel,* Paris: Éditions Salabert

Xenakis, I. (1962), *Strategie*, London: Boosey & Hawkes

Young, L. (1993), *Dream House* [sound and light installation] [online description]. Retrieved from https://www.atlasobscura.com/places/dream-house

Young, L. (1984), *The Second Dream Of The High Tension Line Stepdown Transformer From The Four Dreams Of China* [CD] Gramavision R2 79467

USB memory stick containing porfolio of works, sample recordings and video tutorials