Integrating Plant Electrophysiology and 3D Sonic Art

Queen's University of Belfast

Doctoral thesis

Integrating Plant Electrophysiology and 3D Sonic Art

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i) Abstract:

This thesis accompanies a portfolio of site specific sound installations that were delivered in the UK, Europe and South America between 2012 and 2016. The principle focus of the research is to combine plant electrophysiology and sonic art with a particular emphasis on spatial audio. By using networks of electrodes, audio spatialisation and various artistic techniques, electrical activity in the biosphere was made tangible through sound in real-time. Installations based on this research were presented at public events, immersing listeners in the complexity of these processes. Bespoke software was created to meet creative and technical objectives.

The main research question asks 'How can plant electrophysiology and art be integrated?' The case is made that the artistic and scientific side of this interdisciplinary research should meet on an equal footing, in which art does not occupy a subordinate role to science. The research therefore aimed to create a combination of both fields that enables a genuine dialogue between them. Novel sound installations were created that were designed to stand as works of art in their own right regardless of whether or not the audience knew there was a scientific component to the piece; at the same time new approaches to monitoring electrical activity in plants were developed. A description of how these two elements are combined and how scientific needs influence artistic work and vice versa is given. The case is also made that, for site specific work, the context and location in which the sounds are presented are just as important as the sounds themselves. The principle object of this research is not to gather qualitative or quantitative data, but to convert signals into sound in real-time and create art installations that engender a space where independent elements of both disciplines can merge as well as develop independently from each other. Technical and artistic gaps in the field are identified through the literature review and addressed in the installations. The software created forms a bridge between the creative and the technical side of the research and is described by means of videos. During the course of the research some discoveries were made, that although do not directly address the original research questions, nonetheless form interesting subjects in their own right and potential avenues for future investigation, as such they are included. This commentary is accompanied by a USB stick that has relevant software and audio documentation. It also includes an offline website which contains important information such as videos, and is referred to throughout the text and forms an essential component of the thesis.

ii) Acknowledgements

I would like firstly to thanks my supervisor, Professor Michael Alcorn for his guidance and for supporting me to conduct the research and create the art installations I had dreamed about for years, both in the Amazon rainforest and at home.

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'We are one tribe with bacteria that live in hot springs, parasite barnacles, vampire bats and cauliflowers. We all share a common ancestor.' Richard Fortey

*'Everyone knows sound can't be organized,
eventually it will disintegrate.'*

Todd Dockstader

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iii) PUBLICATIONS: This is a list of material in this thesis that is already published

Leudar, A 2016. 'Surrounded'. Leonardo Journal of Science and Art.

Leudar, A., 2014. ‘An Alternative Approach to 3D Audio Recording and Reproduction’. *Divergence press,* University of Huddersfield, Issue 3.

Leudar, A., 2014. ‘Integrating Plant Electrophysiology and Art’. *ceiarteuntref,* http://ceiarteuntref.edu.ar/leudar.

Leudar, A., 2014. ‘Invisible forest; An Artist's Guide to Plant Electrophysiology’. *Plastir Journal of Science and Art,* Volume 34.

iv) LIST OF WORKS and EXHIBITIONS

‘Notte Blanca’ Aria Art Gallery, Florence, Italy, May 2013

'Invisible Forest (Temperate version)', Sunflower Festival, Ireland, August 2013

'Garden of Membranes 1.0', Clandestino Festival of Contemporary Art, Santa Cruz, Bolivia, June 2014

'The Code' and *'Mycorrhizal Meltdown'* 4th computer arts conference, Rio de Janeiro, September 2014

'Bosque Encantado' Botanic Gardens, Quito, Ecuador, duration: 3 days, November 2014

'*Surrounded*'Sonandes (Bolivia's first festival of Sonic Art), La Paz, Bolivia, Dec. 2014

'Garden Of Membranes 2.0', Naughton Gallery, Belfast, duration: one month, September 2015

'*Involvente'* Cromasomos, Galería Giv Lowe, Lisbon, Portugal, duration: 3 weeks, Nov 2015

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vi) Acronyms:

AP - Action Potential

DAQ - Data Aquisiton Device

DBAP - Distance based amplitude panning

LINV -International Laboratory of Plant Neurobiology

VBAP - Vector based amplitude panning

VP - Variation Potential

VST - Virtual studio technology / software effects plugin

WFS - Wavefield Synthesis

1 INTRODUCTION

1.1 BACKGROUND

I first moved to the Peruvian Amazon in 2001 and since then I have spent a total of ten years in the region. My initial motivation for doing so was to learn the techniques of Peruvian plant medicine from the husband of a friend of mine, Dax Escalante MacMillan. Dax lived in the Amazon town of Pucallpa and practiced medicinal herbalism or 'vegitalismo' as it is known locally. Although Dax was a Mestizo, his clients ranged from the local indigenous Shapibo population to rich urbane Limeños from the capital and the occasional tourist and researcher. In the Amazon region such men and women are considered not as mystics but as the local health service and if their medicines prove ineffective they are quickly disregarded. Although I had been interested in the idea of phytotherapy before arriving in the Amazon I suspected that such cures, when effective, were simply a result of the placebo effect, a kind of faith healing, and that even when particular plants were effective it was purely as a result of thousands of years of trial and error. However, there are several problems with both of these assumptions. Firstly, there are many examples of medicines and poisons which are created by the blending of several different plants that must be boiled together for hours on end to become active. Individually such plants have no effect; perhaps the best example of this is 'curare', an arrow poison which forms the basis of several common anesthetics used in modern hospitals

'*It is necessary to combine several plants and boil them for 72 hours, while avoiding the fragrant but mortal vapours. The final product is a paste that is inactive unless injected* *under the skin. If swallowed it has no effect. It is difficult to see how anybody could have stumbled on this recipe by chance experimentation.'* .

(Narby, 1998)

Such concoctions clearly have an effect that could not be achieved by placebo alone. In a rainforest consisting of tens of thousands of plant species (WWF, 2015) the odds of such a combination of plants being discovered by trial and error alone are extremely small.

Other studies have shown that indigenous tribes which have had no contact with the outside world have very few medicines as there were very few illnesses; it is therefore the opinion of some researchers that many of the cures found in the indigenous apothecary were discovered post-contact in response to the new wave of occidental illnesses (Davis, 1996) (Highpine, 2009). Whilst there is no doubt that the practice is rife with charlatanry, there are still those who maintain an effective knowledge of plant medicines and it is also of note that many pharmaceutical companies use the knowledge of such medical practitioners to form the basis of many modern drugs, with little concern about how such knowledge was acquired (Newman, 1994). When quizzed about the source of such knowledge, healers would often claim they communicated with plants, which they considered to be sentient, to find out what the most suitable plant to cure a certain illness was (Highpine, 2009). Also of note was their use of 'Icaros'; magical songs with which they would sing to plants in order to elicit information or other beneficial effects. Naturally, such beliefs meet with skepticism in occidental culture, but in view of the obvious effectiveness of much of these medicines and their proven economic value, I decided to suspend my disbelief. Exposure to this culture therefore planted two questions in my mind. Firstly, 'Could plants be intelligent and, if so, is there a scientific basis to such a belief?', and secondly, 'Can plants respond to sound?' Whilst these are not my research questions per se and to answer them conclusively falls beyond the scope of the current research, and possibly current scientific instrumentation, they did inspire a burning, albeit naïve, curiosity which formed my main motivation to initiate the current and ongoing research.

As well as consulting scientists at Queen's, during the course of this investigation I contacted some of the leading scientific minds in the field, including Stefano Mancuso at the International Laboratory of Plant Neurobiology, where I stayed for three months. Expecting a skeptical reception, I found the response from plant electrophysiologists to be sympathetic. Researchers in the field of plant electrophysiology explained to me that although the implications of research in their field was astounding, the public is often unimpressed by a scientific research paper and I had many conversations with scientists about how this research could be bought to life through art.

1.2 THE STRUCTURE OF THIS THESIS

There are several introductory chapters that set the scene for the research and describe various elements within it. The literature review delineates both the scientific and cultural context of the research and highlights unexplored areas. Once this background has been conveyed, the research questions are described along with how they relate to unexplored areas in the field and a brief description of how the questions are addressed. After this there is a brief outline on how the thesis makes an original contribution to knowledge. Technical details that are generic to all the installations are described in Chapter 5. Technical details that pertain to a particular installation only, or which were developed in a particular installation and subsequently used in others, are described in the section dealing with that specific installation.

After the introductory chapters, this thesis will unfold chronologically describing each installation sequentially. Each installation, to a large extent, developed out of the previous, adding technical and creative refinements. It therefore seems logical for the thesis to follow these developments chronologically, focusing on what made each installation different from the previous, what problems were encountered, and how the solutions to these problems were addressed in subsequent installations.

The thesis will describe different sound installations, compositions and the software that was created to make them. It will make a case for a more egalitarian relationship between art and science. It will show how the installations, compositions and software address the research questions. Finally, it will critically evaluate the research and discuss what future developments are desirable to advance the field.

Documentation, videos and audio examples of the installations are included in the offline website which is referred to throughout the text. The website can be opened by double clicking the file named 'index.html'. Often the installations would go on for several days and were a visual experience as well as an audio one. The videos provided give more of a sense of the installations than the audio files alone. The software is explained almost exclusively by means of videos; it is therefore essential to watch them in order to understand how the software works. In addition to this audio example, multichannel files and stereo are included in the folders bearing the name of the installation in on the USB stick provided. A speaker map is also provided for each installation in the same folder.

Software for Max/Msp will also be provided on the USB stick in the folder entitled 'software'.

1.3 SUBJECTIVITY

When describing scientific phenomena I try to be as objective as possible. However, during the course of this work, when describing artistic choices and critiques of my own work and the work of others it has been necessary to make subjective value judgments. While I try to maintain a level of objectivity whilst assessing both scientific and creative work it is unavoidable that some subjective value judgments are made, especially when it comes to discussing the aesthetic choices made with regards to a piece of creative work.

2 LITERATURE REVIEW AND CONTEXT OF THE RESEARCH

2.1 AN INTRODUCTION TO PLANT ELECTROPHYSIOLOGY

The first suggestion that there was electrical activity in plants was in 1783 with Bertholon's article '*De l'electricite des vegetaux*' (Bertholon, 1783). Plant electrophysiology was further explored in 1873 after nerves had been discovered in animals. The first plant to be investigated was, unsurprisingly, *Dionaea muscipula* (The Venus Fly Trap) when Dr. Burdon Sanderson released his pioneering paper on electrical activity in the plant (Burdon-Sanderson, 1873) whilst working with Charles Darwin (Darwin, 1888).

There are two main ways of measuring electrical signals in plants (known as action potentials or APs, and variation potentials or VPs) (Fromm et al., 2007). The first is extracellular, which takes measurements from outside the cells, and the other is intracellular which requires one electrode inside the cell vacuole and one outside the cell wall. Ion fluxes can also be measured using vibrating glass micro electrodes (**see offline website > Diary > Linv**). The first extracellular reading was taken in 1873 by the electro physiologist Burden-Sanderson and the first intracellular recording was made in the 1930s by Karl Umrath (Umrath, 1930). For art installations it is easier to use extracellular readings using standard electrodes such as Agcl and graphite with data acquisition devices. Ion sensitive vibrating glass micro-electrodes and intracellular recordings require a high level of specialist knowledge and bulky expensive equipment such as micro manipulators which make them less suitable for use in art installations.

The next significant research into this area was conducted by Indian scientist Sir Jagadish Chandra Bose. Bose was the first scientist to seriously propose electric signaling in plants using APs with a system similar to that of animals (Bose, 1907). He proposed that fibres in the phloem of a plant fulfilled the same purpose as the nervous system in animals in transporting these electrical signals around the plant (Bose, 1926). Despite Bose having being a well-respected early pioneer of radio, his presentations on plants were received with barely concealed ridicule at the Royal Society in London, however, many of them would eventually be proved to be correct. His ideas that plants responded to wounding with electrical signals would be demonstrated over 70 years later by Willdon in his famous paper which showed electrical signals were involved in the inhibition of proteinase as a result of burning the plant (Wildon et al., 1992).

2.1.1 **The not so secret life of plants and telepathic yoghurt**

In the 1960s, significantly more research in this area would be conducted, though the 'maverick' nature of some of the research would put off many serious scientists from researching the area for many years. One popular documentary (and book) that investigated the relationship between plants and sound, amongst other things, was '*The Secret Life of Plants*' released in 1973 by Peter Tompkins and Christopher Bird (Tompkins & Bird, 1973). Many of the experiments included are viewed as poorly controlled (Galston et al., 1979) and 'The Secret Life of Plants' has now been written off as largely pseudo-science. Among the experiments conducted was one which tested the effect of music on plants. Aside from the fact that the experiments were not properly controlled, little thought was given as to why plants would respond to human music let alone the occidental 'well-tempered scale', nor why such a response would allow an evolutionarily advantage. The legacy of this era can be seen even to this day with many artists attempting to convert plant electrical signals into sound using midi instruments and the well-tempered scale (Golden, 2012.). The documentary included a report by the CIA's chief polygraph technician Cleve Baxter who claimed that polygraph tests indicated that plants responded not just to wounding, light and temperature but even to human thought. Many of these claims were refuted by the scientific community in papers such as 'The Not So Secret Life of Plants' (Galston et al., 1979). Baxter caused further controversy by claiming that all life, even the microorganisms found in yoghurt, were in possession of a kind of telepathy causing nearly the entire scientific community and associated funding bodies to shun the entire field for many years (Pollan, 2013).

2.1.2 **The renaissance of plant electrophysiology**

However, despite this stigma, several good studies were conducted during this lull of interest and recently research in this area has been blooming. APs in plants have now been accepted into the scientific mainstream and have found applications in agriculture which use plants as biosensors to monitor environmental conditions (Lehner, 2010) (Pleased, 2014). Although plant APs are generally much slower than those found in animals (usually in the order of mm/s) claims of much faster APs have been made, including one in soya of 30m/s which is comparable with animals (Volkov et al., 2000).

Since the days of Darwin and Bose, much more has been understood about plant action potentials. It has been found that these tiny electrical signals propagate through the phloem due to the opening and closing of voltage gated ion channels across the cell membrane (Tester, 1990) and may propagate through the plasmodesmata of cell walls via the apoplastic pathway. However, unlike animal nerves, the depolarisation of these APs is effected by the release of negative chloride ions instead of the uptake of positive sodium ions (Mummert & Gradmann, 1991).

These signals are extremely tricky to measure for those coming from an artistic background or even a scientific background in a different field. Things are made even more difficult today due to an increase in background electrical noise from gadgets and today's ubiquitous electric technology, despite the filtering of mains electrical frequencies (50/60hz) and the use of a faraday cage. A useful paper for artists interested in measuring these signals is 'Instrumentation for Measuring Bioelectrical Signals in Plants' by Lee Karlsson (Karlsson, 1972). This gives precise methods on how to measure action potentials in plants and includes detailed circuit diagrams as well as information on electrode type and placement.

2.1.3 Recent research that demonstrates that plants respond to sound

Recently there has been renewed interest in the field of plants and sound (Mishra, 2016) (Petraglia & Marcelo, Silveira, 2008.) (Schöner, 2016), though most experiments have been looking at growth patterns (Qi, 2010) (Bochu, 2003) (Tianzhen et al., 2009) and gene expression in response to sound (Jeong et al., 2008). Perhaps the most astonishing recent discovery was that of sounds generated by maize roots (Gagliano et al., 2012). When researchers tested the sound on other maize seedlings they found the roots grew towards the sound. There is also a suggestion that the clicking noises produced are a kind of communication rather than just the random noises produced by the movement of water in the stem. Monica Gagliano from the University of Western Australia, who made the discovery, encourages more research in the field in her article 'Green Symphonies: a call for studies on acoustic communication in plants' (Gagliano, 2012).The article also indicates that 'Icaros', songs sang to plants in traditional Amazonian medicine, warrant further investigation. Amplifying tiny acoustic emissions from plants such as those discovered by Monica Gagliano represents another avenue of exploration for sound art installations that does not involve electrophysiology.

Although many experiments have shown that electronic signaling in plants is common in response to a range of stimuli such as light (Pavlovič, 2011) (Koziolek et al., 2003), pollination (Spanjers, 1981), physical movement (Fromm & Eschrich, 1988) (Bose, 1925) (Sibaoka, 1991) (Herde et al., 1988), temperature (Herde et al., 1988), insects (Volkov & Haack, 1995;) and wounding (Stankovic & Davies, 1998) (Rhodes JD, 1996), to date no experiments that the author is aware of have been conducted which test plant APs in response to sound. To this end the author has begun experiments investigating this area. It is quite possible that they do, especially in tropical plants and especially above 3khz which is the region of the audio spectrum occupied by tropical bird and insect noise. This also presents interesting possibilities for sound installations especially if AP responses in plants can be used to control sound equipment. Some installations which seek to incorporate these ideas are described later.

2.1.4 **Plant neurobiology**

Plant neurobiology is a recent term to describe a new field of plant science. It has caused some controversy with flurries of papers and counter papers arguing for (Trewavas, 2007) (Brenner et al., 2007) and against (Alpi & Etal, 2007) the validity of the term. Eventually, proponents agreed the term should be used as a metaphor in order to avoid anthropomorphising the processes involved (Trewavas, 2007). However, the validity of the term or not may seem pedantic in the light of recent research; no one now denies plants are much more able to compute complex responses to the environment than previously thought (Baluvska et al., 2004). Many scientists in the field now agree that plants can no longer be considered ‘'automata'-like organisms’ and that they can learn, remember and communicate like many other organisms (Falik et al., 2012) (Goh et al., 2003). To many artists and indigenous people this may seem obvious, but, according to Mancuso, for scientists to find evidence of this flies in the face of a deep rooted cultural prejudice in the West that dates back to the time of Aristotle (Aristotle, 2000 bc) (Mancuso, 2015).

2.1.5 The revival of the ‘root brain’

Plants have some of the same neurotransmitters found in humans (Baluška et al., 2009) and, though controversial, something similar to a synapses (Baluvska et al., 2005) (Volkov et al., 2013). They also exhibit coordinated movement including ‘swarm like behavior’ (Baluška, 2010) as well as various forms of memory (Volkov, 2008). Perhaps most interesting of all is the revival of Darwin’s ‘root brain’ hypotheses (Baluška, 2009) which postulates that plants’ root systems are a kind of neural net with most activity being found in the transition zone of the root apex. Similar research into the mycelium of fungi exhibit action potentials, some spontaneously arising without external stimuli (Olsson, 1995). Even more recent studies suggest that plant roots are able to differentiate self from non-self (Gruntman, 2004) and plants can even recognise their kin (Biedrzycki ML, 2010).

2.1.6 Very recent research and unexplored areas

The Mycorrhizal network is a network of fungal mycelia that connect different plant roots together (Simard, 2012). Action potentials have been detected both in the root systems of plants (Baluška, 2004) and the mycelia of fungi (Olsson, 1995). More recent research has shown that plants and trees are able to communicate rapidly across the mycorrhizal network (Babikova Z, 2013) (Song, 2010) (Simard, 2012). Some research has been conducted on electrical activity in the myzcorrhizal network (Berbara R, 2006). Previously, another paper showed 'action potentials in fungal mycelia signaling the availability of nutrients at the tips of hyphal chords' (Olsson, 1995). However, despite this tantalising data, to the author's knowledge no research has been done on whether action potentials can cross from the root systems of plants to the mycelia and back to the roots of other trees via the Arbuscular mycorrhizal network. Although this concept has found its way into popular culture such as the film '*Avatar*', it should be borne in mind that several ideas from the film came about as the result of consultations with biologists. The current research makes some first tentative steps to address this gap by using multi-electrode arrays in the field. Converting these electrical potentials into light and multichannel sound installations by amplifying them and feeding them into a computer program in situ presents exciting opportunities to bridge the gap between science and art. Audio visual installations that make tangible these hitherto unseen aspects of complex electrical plant activity have the potential to engage the public and alter the way they perceive the biosphere of which they form a part; they also allow scientists to see how signals propagate in natural habitats in an audio-visual way that would be hard to replicate in the laboratory. The sound installations in this thesis, which will be described in Chapters 8,9,10 and 11, use this research as a technical basis from which to proceed.

2.1.7 **Reflection**

Anthropomorphisation is frowned upon in science, with some objecting strongly to comparisons of plants to animals as referenced here, but it must also be acknowledged that all life shares a common ancestry (Fortey, 2011) and some fundamental similarities are inevitable because of this. Whether or not action potentials in plants are a result of common ancestry or an example of parallel evolution is not clear.

A synergy of visual and sonic art and plant electrophysiology presents multiple possibilities and avenues of investigation and is a relatively unexplored area. Audio visual art can lead to an alternative, immediate and intuitive method of understanding plant bio-electrics beyond the mere sonification or visualisation of data. It is with these ideas in mind that the following sound art installations were devised.

The challenge of this research is to create something that fulfills aesthetic goals of the artist and yet at the same time maintains rigorous scientific method ensuring that the signals in plants are measured correctly.

3 ARTISTIC BACKGROUND AND CONTEXT:

3.1.1 Delineating the research

Due to the obscure nature of the field, when considering the artistic context of this research I have found it helpful to clearly define what it is not. People who are unfamiliar with this field often contact me with news of a new sound installation involving plants. However, aside from the fact a plant may have been used somehow in the project, the majority of these are unrelated to my field of research in the majority of aspects. In fact the current research has more to do with some installations involving animals and bacteria than plants. In order to clearly delineate the field in which this research is situated three examples will be used. Two are examples of installations that are not closely related and one example is.

Luke Jerram's 'Plant Orchestra'

Luke Jerram created an installation in a Cambridge Botanical Gardens in 2011 whereby tiny sounds in the plants were amplified and played back.

'Although imperceptible to the human ear, plants create sound. Using specialist microphones water can be heard as it flows slowly up the stem of a plant. The sounds created during the day are different to those at night and they alter with the seasons of the year. If trees are suffering from drought, scientists can measure acoustic emissions that occur caused by cavitation and embolism within the plant….. Hundreds of sound samples were recorded from dozens of plants within the glasshouses for the arts project. The best recordings were then played from their prospective plants as part of a light and sound installation.'

(Jerram, 2011)

This investigation is not closely related to the current research; despite the fact that the installations described took place in the vegetation of Botanic Gardens. The reason is that this thesis is primarily an investigation into plant electrophysiology, plant communication and complex electrical activity in plants. Such electrical activity may be indicative of intelligence or, at the very least, complex signaling in plants. Even if the idea of cognitive functions in plants is unpalatable to the reader there can be no question that plants use action potentials as part of their 'signaling' system. Jerram's installation explores an entirely different area: minute sounds that are a side effect of biological functions, not necessarily used for signaling. An analogy would be that the current research would be looking at electrical activity in the human brain, whereas 'Plant Orchestra' would seek to make audible the minute sound of blood passing through veins and arteries. Although 'Plant Orchestra' has a strong scientific basis and involves plants, it has a very different focus to the current research.

David Tudor's Rainforest

Some colleagues have suggested David Tudors '*Rainforest*' is a related work and significant predecessor to this research. In David Tudor's own words:

'Instruments, sculpturally constructed from resonant physical materials, are suspended in free space; each instrument is set into sonic vibration through the use of electromagnetic transducers . . . exciting their unique resonant characteristics. The excited resonances are routed to a conventional audio system by the use of one or more pick-ups attached to each instrument.'

(Tudor, 1973)

Although the work is concerned with a kind of 'sonic ecosystem', has the word 'rainforest' in the title and uses 'experimental sounds', the exploration of resonance and feedback loops it uses has little to do with plant electrophysiology, using art to tell us something about complex electrical activity in plants or plant intelligence, nor does it inform the artistic aspects of the current research as such I do not consider this closely related work.

Paloma Lopez's Interspecifics

'Interspecifics' is a project created in 2014 which turns electrical activity in bacteria into sound and light displays,.

'The interface amplifies the microvoltage produced by these microorganisms transducing their oscillatory features into raw electronic signals tuning the internal clock of the whole system and producing an unexpected array of sound patterns.'
(Lopez, 2014)

This idea of amplifying the tiny electrical signals found in bacteria into sound and light installations is much more closely related to the current research even though it does not involve plants. This is because it aims to sonify electrical activity of ion channels in biological systems that are normally considered 'simple' and aims to inform the audience as to the complexity of such activity.
The next section will look at projects that are definitely related to the current research and show how the current research seeks to fill a gap in the current body of research in the field.

3.1.2 An overview of plant electrophysiology and art

I was not aware of any of the artists in this section before I conducted my literature review, and as such they were not a primary inspiration for this thesis. The main influence on the course of the current research of related work in the field was that I tried not to repeat things that had already been done before and where there were inevitable similarities, to expand upon previous work both technically and artistically. Their work is discussed to put the current research into context and to show how it is different to, or builds upon, previous work in the field. Although I may be critical of some of this material it is only in the interest of advancing the field, and with the full understanding that my own work may receive equally critical appraisal in the future.

Early on in the research it became obvious that there was a wide gap between scientists and artists working in the field of plant electrophysiology. Most scientists I contacted did not take artistic projects incorporating plant electrophysiology seriously at all (Volkov, 2013). Some pointed out to me that to get involved with such projects could tarnish them with the brush of pseudoscience which had nearly crushed the field entirely after 'The Secret Life of Plants' (Pollan, 2013). Artists therefore had limited opportunities to get adequate technical supervision and incorporate it into their practice. Although there is quite a lot of technical knowledge available online, much of it requires months of background reading to understand properly and a fair amount of lab time to convert theoretical knowledge into practical reality. If tackling the subject as an individual, to engage fully with the relatively narrow field of plant electrophysiology the artist must also become an electrician, an electrophysiologist, a computer programmer and a biologist. As most people do not have time for such an endeavor they inevitably reach out to the nearest person in their environment who seems to possess any sort of electrical engineering knowledge. Usually people are chosen as technical consultants for the project even though they had no knowledge whatsoever of the field of plant electrophysiology (Garcia, 2013). Even if an artist should be lucky enough to collaborate with a specialist, even amongst the leaders of the field there is still considerable disagreement and controversy, especially as to what does and does not constitute an artifact. Artifacts in this context refer to errors in equipment rather than true signals. Artists seem to be enamored of the idea that plants are conscious and any electrical activity displayed in their equipment is enthusiastically taken as evidence of such, without a rigorous appraisal of methods, making sure they are not reading artifacts or attempting to find alternative explanations (Mileece, 2012). The idea seems to be deeply rooted within the public imagination as well and any such project is normally received enthusiastically regardless of the robustness of the science behind it. In one sound installation I was setting up received a rapturous response from a group of people walking through the forest, their faces were full of wonder at the sounds being generated by the plants; unbeknown to them I had not even connected the electrodes.

Another issue is that, because the novelty of the work becomes the idea that somehow 'the plants are making the sound', there appears to be less effort put into the aesthetics of the work (Dogane, 2007). I believe it unlikely that much of such work would stand on its own as a piece of music or sound art if it was not for this proviso. When it is taken into account that the plants probably are not really affecting the sound at all such work may be considered as having limited value as either art or science. It should be noted at this point that at the beginning of the research I was just as vulnerable to the above mentioned pitfalls as anyone else and the above criticisms are applied as harshly to my own work as to anyone else's. There have been several artists who have tried to convert plant electrical signaling into sound (Kuribayashi, 2007) (Dogane, 1992) (Henriques, 2011) (Masaoka, 2002, 2009) (Mileece, 2012), as many of them exhibit the similar approaches I will focus on two key representative works. The first, *The Music of the plants* (Damanhur, 2011) discusses the first known attempt to sonify plant electrophysiological data and the second, *Pulsum Plantae* (Garcia, 2013) , is a fairly representative example of work in this field and shall be discussed further in the chapter 'Technical Issues'. I will use these as case studies to illustrate common practice and how the current research attempts to address any issues and do things differently both technically and artistically.

3.1.3 **Damanhur's 'The Music of the Plants'**

The first artists to try and interface plant electrophysiology with sound were an alternative community based in northern Italy known as Damanhur. They first started converting electrical activity in plants into sound in 1976;

'*….when resident researchers created an instrument that was able to capture the electromagnetic variations of the surface of plant leaves and roots, and turn them into sounds*'. (Damanhur, 2015)

I could find little technical information on these early experiments. They appear to have published no academic papers. I contacted Damanhur to try and clarify who were the originators of the project and received the following reply;

'The first group of people working on this project in the late 1970s were Falco Tarassaco (Oberto Airaudi), Castoro Anice, Setter Juta and Valerio Sanfo….. They came up with the ideas to use the electrodes, which were originally wooden clothes pins with cotton on the clips that was saturated with a specially prepared gel.' (Gardenia, 2016)

They recently made a device commercially available known as the 'Music of the Plants' (Damanhur, 2015). Some patents of related devices were filed by Oberto

Auraudi, the founder of Damanhur, and two colleagues, though it is unclear who was the main designer of the original device (Araudi, 2001). In another personal communication with members of Damanhur they informed me that the device worked by injecting a small current into the plant to measure the resistance therein. This resistance measurement is then used to change MIDI notes - the idea being that plants were then able to play music for you in the garden. The immediate technical question this raises is how this electrical signal affects action potentials; however, the information provided was too vague to construct a thorough technical critique. I am not convinced MIDI notes are the best way to produce sound from plants though and producing music with its basis in western classical scales seems myopic and culture bound. Midi notes controlling a midi piano are extremely limited in their range of musical forms, when compared to the full spectrum of sound available to us, or which a plant would normally be exposed to in nature. The end result sounded to me like new age relaxation music (Damanhur, 2011). Whilst it is inevitable that the artist will impose their own aesthetics upon the sounds the plants are allowed to produce, the end result here is so representative of that genre that it can be questioned how much influence the plants could really have on the composition. There was no use of spatial audio in the installations so the sounds would not have given any indication of where signals were taking place.

The use of music is not a new development in human–plant interaction however. In the Amazon, traditional magical songs known as ‘Icaros’ are used to sing to plants. However, these musical forms have developed over hundreds of years specifically with the goal of interacting with the plant kingdom and each song has a very specific purpose (Stephan, 2010); as such they do not constitute an alien musical form imported from a disparate cultural mode. There is increasing evidence of acoustic signaling between plants and animals (Schöner, 2016). It is conceivable that such traditional songs, developed through trial and error over many generations, contain frequencies designed to elicit an array of plant responses. However, any observed effect on plant growth from western classical music is more likely to be due to pure coincidence in that certain music contains certain frequencies and timbres (Petraglia & Marcelo, Silveira, 2008.).

Despite these criticisms it cannot be denied that the researchers of Damanhur were pioneers in this field.

3.1.4 **Soundscape**

There have been numerous other artists working in the area of soundscapes which use a lot of natural field recordings. The most prominent example may be Barry Truax who was one of the originators of the World Soundscape Project (Truax, 2009). Whilst the World Soundscape Project has not informed my work directly, Truax says something that elucidates my approach;

"Most pieces can be placed on a continuum between what might be called 'found sound' and 'abstracted' approaches…..contemporary signal processing techniques can easily render such sounds unrecognizable and completely abstract." (Truax, 2002)

The current work occupies both extremes of this continuum. On the one hand it creates realistic natural soundscapes as authentically as possible; on the other hand these sounds are processed so as to be utterly unrecognisable, or synthesised elements are introduced and then these two polarities are then woven together. There are also occasions whereby less extreme positions on this continuum are occupied. For example natural sounds, presented in a believable context (such as bird sounds coming from hidden speakers in trees) are subtly altered. Perhaps the sound of a bird will land on a branch near your head, but then make a bizarre or human noise instead of a bird call. Slightly blurring the line between the real and the surreal can catch the listener unaware and can be more disorientating that creating more extreme and chaotic sounds.

Truax talks of another continuum which consists of human speech, with its strict syntactic rules and limited array of phonemes on one end, progressing through music ,with less strict syntactic rules, and then finally arriving at the vast plethora of sounds that exist in the world, synthesised or natural and which in his view do not seek to convey meaning and contain no syntactic structure at all (Truax, 1984).

My work perhaps adopts a less anthropocentric position, in that it explores the possibility that the biophony especially that of rainforests, is more nuanced than many people currently believe, and could be possessed of both syntax and quite specific meanings.

More recent attempts to catalogue the authentic sounds of the natural world, specifically the amazon, include '*Fragments of Extinction*' by David Monacchi. I share some of Monacchi's concerns about the state of tropical ecosystems. The work presented in this thesis also creates 3D audio recordings of environments whose sounds are rapidly vanishing and which can be used as '3D audio documents' in the future. Monacchi uses traditional 3D recording techniques in his collection, such as ambisonics (Monacchi, 2011). I present an alternative way of recording such environments in this research that I believe renders a more authentic 3D sonic representation of natural ecosystems.

3.1.5 Sound installations in the trees

In the forest we focus on more on what we can hear than what we can see as our vision is limited by vegetation. In fact research has shown that limiting our vision sharpens our hearing so much that it can even help reverse hearing loss in older people (Petrus, 2014). For the same reason, all of the installations described in this thesis were delivered, wherever practicable, in darkness. As far as I am aware '*Biomes at Nigh*t' at the Eden Project in 2010 (Eden Project, 2010) was the first to make use of 3D audio techniques in the forest and '*Invisible Forest*' (Leudar, 2013) was the first to use trajectory automation in conjunction with 3D audio for ecosystem mapping in the forest. Several artists have delivered sound installations in forests which have speakers mounted in trees that may or may not be hidden (Wright, 2003) (Scanner, 2016). The first person to do this was Ken Kesey with the Merry Pranksters.

'Kesey by now had not only the bus but the very woods wired for sound. There were wires running up the hillside into the redwoods and microphones up there that could pick up random sounds. Up in the redwoods atop the cliff on the other side of the highway from the house were huge speakers, theater horns, that could flood the entire gorge with sound. ….. . machines and things that glowed, winked, hummed, whistled, bellowed, and microphones that could pick up animals, hermits, anything, and broadcast them from the treetops, like the crazy gibbering rhesus background noises from the old Jungle Jim radio shows.'

(Wolfe, 1968)

Whilst I wasn't aware of this installation when I first began working in this area it would be the one with which I feel the most affinity and it bears some resemblance to 'Invisible Forest' with its use of microphones. The conjuring of strange and alien sounds in the forest where vision is limited and the audience is forced to focus on what they hear, not on what they see, is something which is recurring theme in my own work. Where I differ from Kesey is in the use of electrodes, DAQ's, modern effects, automation and trajectories, technology that was not available to Kesey at the time.

Compare this to '*Trees*' by Terry Allen (Allen, 1986) wherein several hidden speakers in two trees emit sounds by musicians such as David Byrne. The sounds are not Allen's own compositions, there is no live element, and there is no attempt at spatialisation other than that provided naturally by separate point sources. The piece illustrates the importance of context; the fact that music is coming from a speaker hidden in a tree, even though if the same music were heard coming from a radio it would not be considered extraordinary, is enough for people to consider it a work of art in its own right.

More recently, in the summer of 2014, '*Living Symphonies*' by James Bulley and Daniel Jones, created a model of the forest ecosystem, different elements of which were converted into musical motifs. It also made use of hidden speakers and spatialisation in the forest (Bulley, 2014). These were not automated in real-time although it did use live weather data to affect sounds in real-time.

3.1.6 **Other artistic influences, artistic lineage**

I do not consider this a composition portfolio in the conventional sense, nor do I consider myself a composer but rather a sound artist which I see as a completely different discipline to that of musical composer.

The discipline of sound artist, or sonic artist, is somewhat ill defined and may vary in meaning according to whom you speak to as is the meaning of 'composer'. For some, sonic arts is an umbrella term that includes any creative practice that works with sound artistically at all, including conventional music (Conlin, 2014). Some also see a composer as anyone who organizes sound, regardless of whether they have any kind of classical training or whether they are making music in the conventional sense (Harper, 2007). In this regard my own perspective is more conservative; a composer is someone who has some kind of traditional musical training, can read music, has a good understanding of harmony and is able to 'make a tune', even if they choose not to do so. My view of what a sound artist is also somewhat narrower than some people's definition. To me, sound art occupies a niche of experimental audio techniques and mysterious explorations into the nature of sound itself, ergot not all musicians are sound artists and not all sound artists are musicians, but some might be.

This is why I consider this a portfolio of sound art installations rather than contemporary classical compositions. Sounds of any description, musical or otherwise, are my 'paints' and the site at which the installation is created is both canvas and paint. I am more concerned with texture, space and cognitive effects of the sounds and site than melody and rhythm. This is not to say there is not a substantial crossover from practitioners of either discipline, nor do I claim that the existence of them as separate entities is anything other than a purely personal and subjective view. However within the context of this research this view may help to provide a frame of reference and points to a lineage that is slightly different to that of a contemporary classical composer, but which I hold as just as valid and requires just as much knowledge and discipline to pursue.

It is tempting to view sound art in this limited definition as similar to sound design; however I would argue that sound design is a different discipline again. Although both disciplines use sound in general (as opposed to music) which may include elaborate effects, sound design is usually created to illustrate a narrative and is usually subordinate to several other elements of a production such as visual ones (Sonnenschein, 2001). A sound artist is just as concerned with the creative core of a piece of work as a visual artist is with a painting, and the work may exist independently from any accompanying medium. This is not always the case, and there are of course many examples where such distinctions break down, such as Michelangelo's murals in the Sistine chapel, which illustrate a Biblical narrative. Nonetheless as a general rule I would argue that sonic art is a separate genre which is somewhat separate from sound design and contemporary classical composition, albeit with some common ground. It is perhaps interesting to note in view of this that most of my favorite 'composers' were trained as sound engineers with little or no classical music training.

Various artists have influenced me over the years and have made an impact on the aesthetic side of this research. Although they are not active in the field of plant electrophysiology, they are nonetheless an important strand of this work. A discography is included after the bibliography with a list of selected key works.

My artistic lineage comes from the subculture of experimental, often self-taught music scene rather than composers from the oft-cited Avant-garde canon such as John Cage and Stockhausen. For many years before I entered university I was autodidactic and published both audio and visual art in what were described as 'outsider' art magazines and media which were also my main influence (Artesian Arts, 2004). Of course it can be argued quite validly that such 'underground' artists themselves had been influenced by some of the great avant-garde composers via a kind of 'trickle down' influence after hearing their work on the radio or in film. Certainly this was the case for late '60s and early '70s 'Krautrock' composers such as Faust and Neu who say they were influenced by hearing composers such as Stockhausen on German radio (Richardson, 2015), indeed two of the founders of Can, Holgar Czukay and Irmin Schmidt, studied with Stockhausen (Van Dusen, 2007). However despite such examples of composers learning both inside and outside the academy, from my own experience, there is a wide disparity in the methods of producing creative work in formal and informal settings, both of which have their advantages and disadvantages. There is also a difference in the way musical knowledge and artistic ideas are acquired within and outside the academy. I have never based new work on the work of others, at least not in a conscious or deliberate manner, though I have endeavored not to 'reinvent the wheel'. The sounds of the natural world, specifically rainforests, have been as great if not greater an influence than any human composer on this work, urban environments always seeming to lack sonic diversity in comparison.

It is the wilder more surreal artists that always captured my imagination and have had the greatest impact on my work. I was always attracted to that which most stoically defied rational or verbal explanation. Stylistically, Hieronymus Bosch was probably the earliest example of a visual artist who represents the kind of art which I aim to produce. His work 'The Garden of Earthly Delights' (see Appendix A) both the inside and the outside of the triptych have resonated with me and bear some similarity to what I do with sound, especially in the current work 'Garden of Membranes' which shall be discussed later.

The visual imagery of Dadaism and Surrealism, Art Brut, Outsider art and Magical art have all left a lasting influence on how I manipulate sound. Conceptual art, though it traces its origins to some these genres, has often left me cold with one or two exceptions. For me the finished result is extremely important and I like to see a high degree of craft in artistic work. Whilst I believe concepts can be powerful, to me they are of secondary importance to the actual object itself; they at least require a well-crafted object to be successfully mediated, and a skillfully wrought object may give rise to a thousand different concepts depending on who is observing it. In this case the 'object' is both the sound and situation in which that sound occurs. Conceptual art rejected the primacy of the object and although an object may be used in the production of a piece of conceptual art, the finished physical object is ultimately of secondary importance with more emphasis being placed on process and ideas. This approach did not provide me with the artistic results I wanted to achieve. I have however adopted some of the trappings of conceptual art, especially with regard to site specificity.

I have therefore rejected parts of conceptual art and synthesized them with some of the aesthetics ideals of art forms that came before it, such as the importance of skill in artistic execution, but using contemporary technology and ideas. Where I do draw from conceptual art is that it has hugely broadened the definition of what an art object can actually be, and that is something I use in my compositions. For example, when I select a place for a composition to be heard in, that place is just as important as the sounds that I make within it, so it is selected as carefully as any source sound. However, where I diverge from the narrative of British conceptual art, is that although I might have a broad view of what constitutes an objet d'art, I consider the aesthetics of the object itself as very important. Craftsmanship is an important aspect of these installations; the choice of environment on its own would not be enough, even if it were to be considered a creative decision.

The rejection of conceptual art could perhaps be perceived as 'old-fashioned' or conservative, hearkening back to earlier times, or 'Stuckism'. However aside from the fact that Stuckists consider only painters as true artists (Childish, 1999) my work seeks to use contemporary techniques. Although some pre-conceptual artistic values are revived, they are combined with some aspects of conceptual art. As this is a case whereby the most recent art form has been partly rejected and combined with its predecessors, this can be considered a dialectic process and signifies entry into new artistic territory. Here, the notion that concept and process is more important than the finished object itself is rejected, yet a broad definition as to what artistic objects can be, and what mediums consist of, is maintained and coupled with the use of the most innovative technology available to create new work. To date I have not found the name of a movement or a manifesto that represents these ideals.

3.1.7 **Musical and sound art lineage**

With regard to sonic art and noise, Luigi Russolo's Art of Noises (Russolo, 1913) is an obvious starting point. However, after spending time in the Amazon, I found myself more interested in sounds found in natural environments, than those that may have come about as a result of the industrial revolution. Later I found myself more enamored of Pierre Schaeffer's 'Musique Concrète' approach than that of Stockhausen's Cologne School, preferring to form theories after the event if at all (Reydellet, 1996). The way the sound installations are presented, with speakers hidden in the undergrowth, owe something to the central concept of acousmatic music in general in that the source of the sounds cannot be seen. Indeed the Amazon rainforest itself, which provided many source sounds for the installations, could be looked at as one of the world's most fantastic and deceptive acousmatic performances, noises that resemble huge cats growling turn out to be moths, and gentle coughing sounds can turn out to be jaguars, and in general the source of sounds in the rainforest are completely unidentifiable to the novice.

When other artists have influenced me it has been a subtle long term influence over many years that has contributed to the atmosphere of some of the pieces, and this is often only obvious after the event. Even then I question as to whether the piece has been influenced by other artwork in the field or if rather, both I and the other artists whose work I feel shares any similar aspects to my own, have in turn been inspired by the same source material, the same dreams or the same sonic worlds.

Those who have had an influence on the artistic side of my work come from a variety of disciplines including literature, painting and experimental music. In the field of experimental music most of them could be described as composers who were 'led by the ear' in that they chose sounds purely because they sounded pleasing or unusual to them and not because they rested upon a theoretical framework. In this way their approach is more similar to Musique Concrète, though few of them developed detailed theoretical models after the fact as Schaeffer did.

Music I listened to early on in my practice ranged from Throbbing Gristle to Shostakovich, though the former would have been a stronger influence. Experimental psychedelic music from the 60s onwards was a large influence as was techno and ambient and drone music during the nineties. Delia Derbyshire and her constant desire to experiment with new sounds and new technology has been a big influence on the kind of sounds I use. In particular her collaboration 'Electric Storm' by White Noise, of which she formed half, was an influence on the work described in this thesis. Todd Dockstader is another composer who adopted a maverick approach to sound and has been an enormous influence over the years and who influenced some of these installations, especially 'Mycorhizzal Meltdown'. The constantly shifting and surrealistic forms of Bernard Pamaigianni's 'De Natura Sonorum', whilst might not being a direct influence on my work, certainly felt familiar to me when I listened to it for the first time recently, with its exploration of the more bizarre yet coherent sounds that can be produced by experimental techniques. 'Not Available' by the Residents has been an enormous influence, not so much in terms of its sonic palette, but rather its celebration of the ineffable. Finally the drones and curious ambiences of Coil's 'How to Destroy Angels' and 'Contaminated Songs' have been gently washing over my subconscious for the last four years and have no doubt had a part to play in my choice of material.

There are several books that have had more influence over this portfolio than any musician or composer. These authors create surreal worlds which combine advanced technology with organic material and nature. The fantastical mechanical forests, hybrid technologies and mysterious atmospheres of books like Jack Vance's 'Tales of a Dying Earth' and Michael Moorcocks 'Dancers at the End of Time' provide a taste of the kind of world I was trying to create with 'Garden of Membranes' and 'Surrounded', a world that was very natural, yet also melded with highly advanced technology in order to create hybrid bio-technological artifacts. The dark atmosphere of Mervyne Peake's 'Gormenghast' echoes the gothic elements of some of the compositions. Several painters present correlated themes and motifs though I consider my work to be inspired by similar source material rather than the painters themselves. Specifically something similar to M C Escher's use of negative space plays an important part in the composition of the pieces. Sometimes the shapes of the silence in a piece can create sonic entities as much as the sounds themselves. I used synthesis techniques where the presence of a frequency in one sound would cause it to be cancelled in another sound, in this way sound objects hollowed each other out. In highly dynamic sound scenes this could create some interesting effects.

The outer cover of Hieronymus Bosch's triptych 'The Garden of Earthly Delights' somewhat resembles the centre piece of 'Garden of Membranes' one of the installations that shall be discussed later.

3.1.8 **Related personal work**

My first experiments which aimed to convert electrical activity in plants were part of my final year project for my undergraduate degree. My tutor watched cynically as I attached a multimeter to a plant and a max patch as unpleasant sounds of randomised sinewaves filled the room. The project was both technically and artistically redundant.

My first attempt to create a surround sound rainforest was in 2004 when I created an eight channel piece from sounds recorded in the Amazon. In 2010 this became a much larger project when I filled four acres of the Eden Project's Tropical Biome with Amazon and South East Asian rainforest noises (Eden Project, 2010). Extensive use was made of spatial audio and the effect was to create the real sensation of being in the rainforest but with imaginary elements included in the composition as well. However, these projects did not use 'spatial audio mapping', a technique described later. The visual aspect and context of the installations was extremely important; if the rainforest had not looked so impressive the sound would not have worked as well. Important lessons were learned at this installation, which have been developed in this portfolio. For example, on one occasion a child was wandering around the forest, most impressed with all the living things that he could hear. Upon seeing a speaker that had not been well hidden he frowned in disappointment and declared that it was all fake, just sounds coming out of speakers. Though a seemingly insignificant detail, the location and context of the work and hiding technology has become an important aspect of the installations and significantly affects people's experience of them, especially in site specific work. Work by Kristian Tyléna has shown that the context in which an object (or, in this case, sound) is perceived is extremely important to our experience of that object (Tyléna, 2011). Such cognitive cues are played with throughout the installations. As this is a multidisciplinary thesis spanning both art and science, I will show how both these aspects of the work have advanced and make the case that art need not adopt a subordinate role to science in multi-disciplinary research, and that if the artistic and the scientific side of the research are to truly combine, they must do so from positions of equal authority.

During the same time period of this research I created several other sound installations such as 'Heaven and Hell' at Glastonbury Festival and 'The Stone Tapes' at the Giant's Ring in Belfast, although they are not included as part of this portfolio as they are not directly relevant to plant electrophysiology. However, they may provide some context for the artistic side the work included in the thesis and as such they are included in the 'Appendix' folder on the USB stick under 'Other Installations'. Materials and documentation such as publicity and photos can also be found in the offline website under the heading 'Diary' which also serves as part of the appendix.

3.2 RESEARCH QUESTIONS

This research builds on previous work in the area, both artistically and scientifically, and investigates unexplored areas identified in the literature review. The original idea was to sonify electrical signaling in plants in real time, and indeed this forms the bulk of the research. Towards the end of the PhD other areas were developed such as data logging, replay and time-lapse electrophysiology.

The end result is not only the creation of new compositions but also new software frameworks for creating and generating compositions, and increasing awareness of electrical signaling in plants. Previous work in the field has been considered and my thesis seeks to improve and build on previous work, investigating areas that have not yet been developed. As an artist my principle medium is site specific 3D immersive multichannel sonic art. Spatial audio and 3D sound therefore forms an important part of the creative side of the work as does the location in which it takes place. Perceived deficiencies and gaps in the field have been analysed and provide the framework for the research questions. The main research question is:

H**ow can plant electrophysiology and art be integrated?**

A series of research questions provide a basis on which new contributions to knowledge are based. A list of research questions is provided along with a description of how the research addresses them:

1. **Sonification of data is an established scientific tool, but it is not a creative practice; how can sound art represent data whilst still maintaining the aesthetics and other considerations involved in artistic practice?**

   The research looks at novel ways of converting electrical signals into sound in ways that create works of art that stand on their own rather than just sonifying data. Further details on how this is done are given later on in the commentary.

2. **How can sound art contribute to scientific understanding?**

   Although it is known that plants send signals to each other, and that electrical signals are an established signaling system in individual plants, no attempts have been made either in artistic or scientific fields to see if electrical signals can travel between plants in ecosystems such as through a forest network. Can artistic practice contribute to a better scientific understanding of if, and how, these signals travel through networks?

   The research develops systems which can sonify action potentials in an entire ecosystem (e.g. a forest network) giving a greater sense of how and where electrical signals are taking place by creating systems that integrate spatial audio with plant electrophysiology; for example audio spatialisation software that focuses audio activity on the same areas where there is electrical activity in a forest network.

A new multichannel time lapse and data logging system is described and used. Software is developed that allows the immersion of the listener and allows the analysis of multi frequency response of electrode channels.

3. **How can this research inspire artistic work in the field of spatial audio?**

This research creates immersive audio environments which use novel spatial 3D sound techniques and incorporate plant electrophysiology.

Novel spatialisation techniques which inspire unusual compositional structures are developed; these in turn inspire the development of a system for tracking electrical signals as they move around the forest in real time.

Miniature spatialisation is used to reveal electrical activity in a Bonsai forest, but also inspires the production of unusual sonic environments

Technical errors in artistic practice often mean that the real electrical signals in plants are not being read. This is one of the major impediments that stops the field advancing and which causes scientists to steer clear of artistic projects. How can this be improved?

The research observes common technical issues in previous and current artistic work that prevent real signals being properly read and ,with the advice of electrophysiologists in the field, looks at ways to remedy them.

3.3 HOW DOES THIS RESEARCH MAKE AN ORIGINAL CONTRIBUTION TO KNOWLEDGE?

1. The work created new ways of sonifying plant electrophysiological data.
2. The work addresses technical errors made by previous artists and attempts to deliver installations with a more robust scientific basis.
3. The work creates a new system for detecting and making tangible the movement of electrical signals in a forest network that has not been attempted before.
4. The work uses novel techniques for creating 3D audio environments for use in sound installations
5. The work experiments with miniature multichannel audio installations that have not been tried before.
6. The work experiments with bespoke ecosystems (a bonsai forest) with these miniature sound installations to allow a more controlled environment.
7. The work creates novel immersive environments using experimental audio techniques combined with cognitive techniques.
8. The work creates a new compositional tool that allows one to immerse oneself in different frequency bands of one analysed electrical signal in the plant.
9. The work creates new software frameworks that can form the basis of future research and development.

4 METHODOLOGY

As this is an interdisciplinary PhD combining science and art, this is reflected in the methodology. With regards to specific methodologies, firstly it is important to note that this PhD does not gather qualitative or quantitative data and is largely 'practice based'.
I will briefly describe some of the thought processes that led to the decisions I made in this regard.

4.1 SCIENCE

This research does not seek to prove or disprove a hypothesis. Rather it seeks to take steps in developing software and approaches that may allow various hypotheses to be tested with future work and aid in the production of sound art installations which convert electrical signal into sound in real time. They could also be used non-creatively to simply monitor electrical or other signals in the ecosystem without any artistic intent. The materials and methods used are clearly described in order that they can be repeated by others interested in doing so. The idea is to not only to make them repeatable but also to openly allow others working in the field to identify any faults in experimental and technical design and hopefully improve upon them by being as open as possible about the techniques used. This is something that is almost entirely lacking in other artistic practice in the field; artists rarely make a detailed account of the techniques by which they read the signals known. Materials and methods are described as necessary within the chapters describing the individual sound installations and also in the chapters 'Technical issues' and 'An alternative approach to 3D audio recording and reproduction'. I have identified some gaps in the literature, such as how it would be possible to monitor electrical signals in a network and not just one plant, and tried to create systems that develop these areas, whilst still being compatible with creative practice.

4.2 ART

There is some debate about the difference between 'method' and 'methodology' in the arts and humanities and considerable controversy over what exactly is an appropriate methodology for practice based research. On this Seago says;

'For…..research in which the end product is some form of art and design practice or an artefact,and in which the research is, in effect, embodied in that artifact….
The main problem facing these research students is that for them, unlike their peers researching into or through art and design, few if any methodological models exist around which they can begin to structure and organise their research work. Indeed, these students are most likely to feel some hostility towards conventional academic research methodologies which they regard as inappropriate to a process of creative, artistic discovery…….. the demand for methodological rigour is difficult to meet in a field in which few, if any, methodological precedents exist. ….
MPhil and PhD students researching for art and design are therefore forced to be methodological trailblazers, and this can be a daunting prospect unless they have very competent supervision.'

(Seago, 1995)

Bearing this in mind there are several other issues with some standard academic and scientific methodologies with regards to the arts that I have considered. Firstly, one of the goals of methodology in the natural sciences is to allow it to be 'repeatable' or to form theories based on the objective statistical analysis of empirical facts or qualitative or quantitative data. Conversely, whilst I do have an artistic methodology, which is described later, ideally using this methodology would lead to different results depending on the artist. If the goal of creating new artistic work is to create something original and that expresses the unique imagination of the artist, to 'repeat' such work in the same way would not be to confirm the validity of the results, as it would in science, but could in fact be viewed as copying someone else's work.

The idea that science is based on reason and art on intuition and imagination, is perhaps unfair to both fields. However, the mechanisms that give rise to the current artistic work are essentially non-verbal, sensory and to some degree, by necessity, subconscious. On self-reflective practice, Brookfield says;

'The process of reflection-in-action is essentially artistic, that is, the practitioner makes judgments and exercises skills for which no explicit rationale has been articulated but in which she nevertheless feels an intuitive sense of confidence.'

(Brookfield, 1986)

However, whilst the processes involved in my artistic practice can be articulated verbally, it is perhaps obvious to note that this articulation is very much the map, not the territory; in other words in the case of these sound installations the territory cannot be based on the map, any more than a mathematical formula can be based on a purely verbal thought process.

As much as possible I have tried to insure that I am not 'reinventing the wheel' and made sure that I am applying art to plant electrophysiology in a way that hasn't been tried before. I have been determined from the outset, however, that the artistic side of the research should not be subordinate to the scientific side of the research; on this Born says,

'…Whether motivated by accountability or innovation, in the trajectories of UK artscience that we have sketched, interdisciplinarity is uniformly conceived in the terms of what we have called the service-subordination mode, auguring hierarchical relations in which art is enrolled in the service of science.'
(Born, 2013)

When describing art science research at 'ACE', Born talks of an art science research project 'PigeonBlog' as a more balanced example of interdisciplinarity;

'Rather than adopt the service-subordination mode …. PigeonBlog makes a scientific contribution, while reconfiguring the objects both of art and of scientific research.' (Born, 2013)

This then more closely describes the approach I had to integrating these two fields, however whilst I notice that even though Born is critical of 'the service subordination mode of art in service to science' and it is clear from her example 'PigeonBlog' how the artistic side of the research had advanced the scientific side, it is not clear how the scientific side of the research had advanced the art.

I wanted the art to further the science, the science to further the art, and for them both to advance as independent entities. For example, I would be presented with a scientific problem, how can the extent and patterns of electrical activity in a forest network be ascertained? A creative solution would occur; I would map the network with sounds. This in turn would provide inspiration for novel spatialisation techniques and act as a springboard for less prosaic and more experimental artistic inventions concerned more with aesthetics and nonlinear processes. In many ways the scientific data and research becomes the site around which I create a 'site specific' composition. Just like a physical location, the scientific side of the research had its limitations, components, implications, requirements, technology and territory. As well as converting signals into sound, my goal creatively was to create soundscapes that I felt fitted this territory and these sonifications, in much the same way as I would with a physical location. As such not every sound in the installation was produced by electrical signals, some just fitted with the sounds generated by the plants or the site in which the installation took place. In some cases the artistic side of the research might take the lead; I might have an idea for a soundscape and then try and get the sonified signals to fit in with that. Again, Born comments on this;

'*particularly in the UK, funding has often been predicated on the notion that the arts are expected to provide a service to science, rendering it more popular or accessible to the lay public, or enhancing and publicising aesthetic aspects of scientific materials or imagery that might not otherwise be appreciated or known. Ironically, our research suggests that in the microsocial space of interdisciplinary practice the hierarchy entailed in the subordination-service mode can be inverted. In art-science, for example, scientists sometimes adopt a service role for their artist collaborators, providing resources and equipment that are used to further a project conceived largely in artistic term.*' (Born, 1995)

4.3 SCULPTING SOUND

My main creative process and methodology is perhaps best described using sculpture as an analogy. Sonic sculpture means several different things and practices. Here it is describing a quite literal process. In sculpture, the idea exists that the finished sculpture is somehow innate in the raw materials and that all the sculptor does is chip away at the unwanted matter until the finished form is revealed. This idea was first attributed to Michelangelo when asked how he carved *David*, he is supposed to have replied;

'It is easy. You just chip away the stone that doesn't look like David.'

It is disputed that he never actually made this remark and the identity of the true author is lost. The nearest definite quotation of this sort from a definite source was found in the Methodist Quarterly review in 1858:

'It is the sculptor's power, so often alluded to, of ***finding the perfect form and features of a goddess, in the shapeless block of marble; and his ability to chip off all extraneous matter,*** *and let the divine excellence stand forth for itself. '*
(Carlton, 1858)

Regardless of the source, the concept nonetheless holds true for my own work. In my own work I normally start off with a raw 'block' of chaos, randomly generated noises, accidentally captured field recordings and other methods for inducing random elements in the composition. Allowing random elements to affect the composition permits serendipity to create unusual sonic structures. Generally I would select things that I hadn't heard before, or that I felt were particularly apt for a certain situation. . In this case the signals also contribute something else that is out of my control. By allowing such uncontrolled elements to have a large influence on the basis of a composition, structures and patterns that I would not have created myself are able to come into being. By allowing external influences to affect the piece, I am able to co-create something that exceeds the limits of my own mind, and in some ways allow external agency to act upon the work. From this raw block of randomised sounds a dialogue begins between myself and the material. I chip away at the parts that I consider extraneous to the pattern or structure I have perceived in the chaos until I have bought it into a more defined and clear relief. In many ways this structure once extracted then acts as a problem which I have to resolve, and the rest of the composition becomes an exercise in problem solving. As the initial parameters have been set, balancing the composition becomes almost automatic, as if I am receiving a set of instructions from the material. Sometimes it is almost as if the composition is creating itself and that I am occupying the role of observer, enabler and paintbrush rather than composer and artist. I continue to make refinements until the finished piece resembles something that I am happy with or that feels complete.

In the case of my practice medium, 3D site specific sound art, the process is also similar to sculpture in that the finished pieces occupy a 3D space and have an important visual and physical aspect to them as well.

Ultimately, the research seeks to engage with two very dissimilar fields in a way that enhances both. It seeks to follow strict scientifically verifiable practice within the field of plant electrophysiology, whilst at the same time allowing the artistic side of the work to indulge in the farthest flung reaches of the imagination, by feeding back these two approaches into each other a synergy of both allows new work to come into being and new ground to be broken in both fields.

4.4 DELIVERABLES

The goal of this research is to create new artwork which integrates plant electrophysiology and sound art, spatial audio in particular and new software systems for creating such work. It also seeks to explore the possibility of creating artworks that reveal something about the activity of electrical signals in plants and ecosystems. However, the main focus of the work is to create installations that do this in real-time, not to gather data for later analysis. The deliverables are therefore sound installations and software.

The next section will now present solutions to some of the technical issues mentioned earlier in this chapter with regard to previous artistic work in the field.

5 TECHNICAL ISSUES

One might think that such considerations better belong in the appendix of a thesis. However, seeing as most electrophysiologists I spoke to regarded lack of technical diligence amongst artists as an impediment to progress in the field (Volkov, 2013) (Rodrigo-Moreno, 2013) (Shabala, 2013), and as a significant effort has been made in getting this side of the research as correct as possible, it is necessary to outline the technical problems encountered and the solutions proposed.

As well as with technicians at Queen's University Belfast, I spent three months consulting and collaborating with plant electrophysiologists at LINV (International Laboratory of Plant Neurobiology) in Florence, Italy and throughout the PhD contacted several specialist electrophysiologists in an effort to properly read electrical signals in plants and eliminate artifacts. The following chapter is a result of these consultations. The picture derived from some of the foremost experts in the field demonstrates there are still many aspects of the field that are not clearly understood and still exhibit considerable controversy. This chapter seeks to pass on further corrections and observations made by various engineers and electro-physiologists in reference to the development of the author's own techniques and those already practiced by other artists in the hope that they will be of use to others working in the field. They are no doubt not perfect either and hopefully future developments will see further improvements in this area.

The Chapter will start with a technical critique of a project which represents a fairly typical example of this kind of work:

5.1 CASE STUDY: MEMORIA DE TALLER, PULSUM PLANTAE

Pulsum Plantae (Garcia, 2013) was an installation at the Ixcateopan gallery in Acapulco, México in 2013 by Leslie Garcia. During my stay at the LINV (International laboratory of Plant Neurobiology) in Florence, electrophysiologists pointed out several obvious technical errors with the project and made it clear that it could not be assumed it had a robust technical basis. It would appear to use a galvanometer to measure a response in plants. Galvanic skin response was used as part of Cleve Baxter polygraph lie detectors (Tompkins & Bird, 1973). They basically measure electrical conductivity on a person's hand which varied according to the amount the sweat secreted, as it was inferred that sweat was a side effect of the stress of lying. To use this to detect sentient responses in plants makes little sense; plants do not sweat when they are lying. They do however release water via their stomata through the process of transpiration. This, however, is more indicative of environmental conditions and how much carbon dioxide they need to absorb for photosynthesis, than how a plant is reacting to external stimuli. Due to concerns about interference from humidity in other factors with readings I eventually abandoned using surface electrodes in my own projects. Nonetheless Cleve Baxter's polygraph experiments continue to inspire and even form the basis of many such art projects. There is a video linked to the project and can be viewed on the accompanying offline website. It is essential to watch this video whilst reading the following section (**Offline website > Case study**). At different points in this video when a response in the plant is claimed will be used to illustrate technical issues that were pointed out to me and which I subsequently tried to avoid in my own work.

5.1.1 1 min 7 sec: Plants respond to touch or proximity

This is a common assertion by artists (Masaoka, 2002) (Mileece, 2012). It is well known that *Mimosa Pudica* (the sensitive plant) and *Dionaea Muscipula* (the Venus Fly Trap) generate action potentials when touched, and other plants may do as a result of thigmo-tropism (Burdon-Sanderson, 1873), which is the change of growth in plants in response to contact (Mordecai, 2002). However, in most cases the readings artists are taking are not the result of a reaction in the plant at all. What is really happening is that the human body's own electrical field is using the plant as an earth, so the electrodes are really responding to the electrical field of the person touching the plant and are not reading a response in the plant at all. In fact, you can get the same results by touching a piece of damp cloth with the same two electrodes in it.

As one plant electro-physiologist put it:

'Earthing may be not the best term but yes it is an artifact, when you approach or touch the plant, you are changing its capacitance, and this is picked up and amplified. Nothing to do with what the plant's sensing.'

(Shabala, 2013)

Another electrical engineer explained:

'What is really happening is that when touching the plant a current path is created between the plant and the body and this can lead to an alteration of the plant's electric field. Consequently the electrodes are responding to this variation and are not reading a response in the plant at all.'

(Massi, 2013)

In scientific experiments a plant is usually put in a faraday cage to ensure there is no electrical interference from the surrounding environment (Jörg, 2007) (please see the included video 'correct way to read action potentials in plants'). In such laboratory experiments it is a cardinal sin to touch a plant as it is well known that the human body's electrical field will affect the readings. Proximity to a plant can also cause a change in the readings for the same reason. Sometimes, such as in the cited video, it is claimed that plants exhibit different strengths of electrical response depending on how hard or softly you touch them (Lepp, 2013); again this is simply because the harder you touch something, the better contact there is between the skin and surface being touched.

New research also reveals changes in gene expression minutes after a plant is touched (Van Aken, 2016). However, these are electrophysiological phenomena. In general it is advised not to touch plants or even go near them if a faraday cage is not being used, as despite the seemingly dramatic response it provokes in electrode readings, it is misleading and deprives the artist of an opportunity to present the true electrical processes happening within the plant. If a faraday cage is not desirable then as much electrical activity in the environment as possible should be removed, the plant should be kept well away from any mains current, and equipment such as laptops should run off battery power if possible . Filters which remove 50 Hz and 60 Hz (mains) should also be used in all cases – some electro-physiologists recommend a low pass filter as low as 20 Hz, while others recommend band stop filters. **See software related to this in the Software folder on the USB drive in the folders marked 'Signal Conditioning' and 'Multi Frequency splitter'**

5.1.2 1 min 20 sec: The plant appears to respond to sound

It is not clear here that this is happening at all and in the short part of the video that does show a response to the sound of a hand clapping, the hand is seen to touch the plant. Again the proximity of the hand to the plant may elicit a change in capacitance as well.

5.1.3 1 min 35 sec: Plants are responding immediately to changes in light

Although this may be possible, these fast dramatic responses to changes in light displayed by some artists can be the result of the measuring equipment being on the same ground loop as the lights – so turning them off or on results in a spike in electrical measurements and is misinterpreted as a response in the plant. This project does not make it clear that this has been considered. I was advised that filtering mains electricity is recommended and wherever possible to run equipment such as laptops from batteries (separate from the light).

5.2 TECHNOLOGY AND AESTHETICS

One common theme in this and many similar works that use a lot of equipment is that of plants in jars, surrounded by machinery and technology. From my perspective this symbolises the idea, albeit subtly, of man’s dominion over nature by means of technology. I preferred to reverse this aesthetic in my installations, conducting them in the field where the technology was visually overwhelmed by the plants themselves. Preferably any technology was completely hidden, with the ultimate objective of combining the natural and the technological in one balanced hybrid system.

5.3 OPERATION AMPLIFIERS

It is recommended that any operational amplifiers used to measure electrical signals in plants have an input impedance of at least 10 gigaohms (Keithley, 1998). The reason for this is that electricity takes the path of least resistance; if the measuring equipment being used offers less resistance than the plant, any electrical signals in the plant will flow into your measuring equipment instead of continuing their natural course through the plant. This obviously makes it impossible to take accurate readings.

5.4 CONSTRUCTION OF OP AMP CIRCUITS

These units were designed by electrical engineer Matteo Massi, and constructed by Massi and I at LINV in Florance. These units were designed specifically for this sound installation and for reading action potentials in trees in the field. They were also used in all subsequent sound installations.

Each op amp unit consisted of a printed circuit board **(see fig. 5.1)**, two capacitors (to reduce battery noise), one TL071 op amp, two 0.1Uf ceramic capacitors, one photoresist PCB, two 9V batteries, wire and a plastic box to house it .

We printed the circuit boards ourselves using light sensitive PCB techniques and acid to corrode copper. The op amps in this unit need to have a very high input impedance to prevent the measuring device itself affecting the measurements. In this case we used a Texas instruments TL071 op amp (in future it would be preferable to use a TL061 as it consumes less power). Each unit was powered by two 9v batteries and consisted of two inputs and one output.

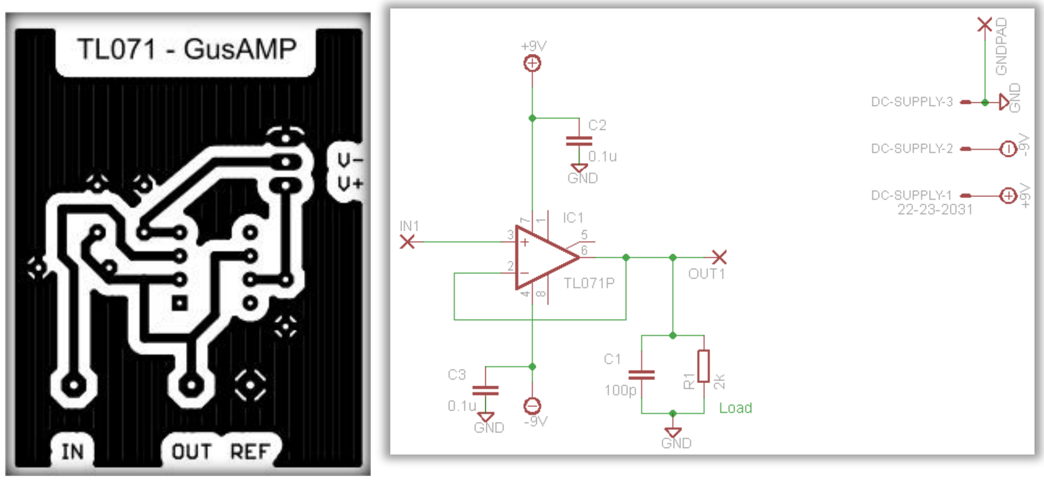

Figure 5.1 PCB and schematic to be opened with 'Eagle' software. See appendix B for larger version

5.5 Electrodes

Electrodes should be non–polarisable and should damage the plant as little as possible. Polarisable electrodes mean a charge can develop between the negative and positive acting as a kind of battery. Wounding in plants produces action potentials (Wildon et al, 1992) so it is advisable to let a plant rest for a while if using invasive electrodes before taking any reading. AgCl electrodes are generally recommended for both invasive and non-invasive electrodes. For non-invasive readings non–polarisable Ag/AgCl pelleted electrodes can be used with ECG gel maintaining contact between the electrode and the surface of the plant (Mancuso, 1999). However, it should be noted that precipitation and humidity may cause considerably increased distortion of the readings. For trees, graphite electrodes can also be used with ECG gel to increase conductivity by drilling a hole in the bark. It should be noted that for invasive electrodes scar tissue will eventually form around the electrodes which will affect readings as electrodes will become insulated from currents in the plant; this should be taken into account if a long term art installation is planned.

The reference and working electrode should generally both be placed in the same tree/plant or the reference electrode can be placed in the soil. Crocodile clips are inappropriate for measuring small electrical signals in plants.

5.6 DATA ACQUISITION

Action potentials in plants can last for 200 ms, though some electrophysiologists say they can be much faster, less than 20 ms (Volkov, 2006). It is important to take into account Niquist-Shannon theorem when taking measurements. Niquist theorem states that when an analogue waveform is digitized both the peaks and the troughs of the waveform need to be sampled as it is the difference in value between these two points that gives the frequency value when interpolated (Marks, 2012). Therefore only frequencies below half the sampling rate will be recorded. Taking this into account, to read an electrical fluctuation or signal of 200 ms you need a 10 S/s sample rate (5 doubled due to Niquist), however in practice I was informed by several electrophysiologists that it is better to have a sample rate 10 times faster than the signal you are trying to read for better resolution – in this case 100 S/s. Many standard multimeters used by electricians only have an sampling rate of 4 S/s and are therefore far too slow to measure action potentials in plants (though they could measure variation potentials or VPs which are longer and slower). It is necessary to bear in mind that on most DAQ (Data Acquisition Devices), Arduino, etc., the sampling rate is divided amongst all the analogue channels so if a DAQ has a 500 S/s overall sampling rate and you are using 8 channels, each channel will have a sampling rate of less than 100 S/s.

If very high detail of the action potential is required for some artistic reason much higher sampling rates would be required.

5.7 DAQ

The DAQ used in all these installations is a Labjack U3 LV. This can have up to 16 channels and has a lower voltage range, more suitable for the smaller voltages found in plants. The Labjack DAQ has a specially made external in MAX/MSP produced by Labjack for the purposes of these sound installations.

5.8 CABLING

In situations where there is a lot of ambient electrical noise or long cables, differential readings can be made using two analogue inputs rather than single ended readings - this uses phase inversion to cancel noise in a similar way to an XLR audio cable. This type of setup uses two cables but only one has the signal you want to read, the other is not connected to the electrode. Both cables will feature the same background noise in them, when the reading from the cable without the signal is inverted and subtracted from the cable with the signal, due to the effect of 'phase inversion' the noise is removed.

Shielded, single core low loss cable should be used if the measurement device is far away from the electrode. In this case the op amp should be placed close to the electrode with the longer length of cable between the op amp and the DAQ. For long cable lengths electrical engineers have advised me that multicore cable can cause phase problems with tiny electrical signals and is best avoided (Rafferty, 2014).

5.9 CALIBRATING THE EQUIPMENT

To ensure that the equipment is correctly reading the signals, the Venus Flytrap *Dionaea muscipula* is used. Electrical signals in *Dionaea muscipula* have been known for well over 100 years and its electrical properties have been the most widely studied of all plants (Burdon-Sanderson, 1873). By placing electrodes carefully near the base of the plants 'mouth' electrodes should be able to clearly read the signal when the plant's three 'trigger hairs' are stimulated. This causes an electrical signal to be sent and the trap to close. This signal should be clearly visible when the trigger hairs are touched within twenty seconds of each other. We can tell this isn't simply the electrical activity caused by interference of the hair triggering implement because this signal should only show once all the trigger hairs have been touched.

6 INTEGRATING PLANT ELECTROPHYSIOLOGY AND ART, NOT JUST THE SONIFICATION OF DATA

6.1 SOUND PROCESSING TECHNIQUES AND CHOICE OF SOUNDS

When converting electrical signals in plants into sound, one is faced with a simple yet important choice - what kind of sounds should the signals control? Reading electrical signals in plants is quite similar to ECG readings of a person's heart in a hospital. In the case of an ECG machine a simple beep is mapped to an electrical signal in the heart. This though is purely functional; the straightforward sonification of data, with no intention of being artistic. Within the context of sound art this mapping becomes a creative decision and is a place where art and science can truly combine.

As previously discussed, common choices made by artists in the past with this kind of work were to use the signals to trigger midi piano notes. Others have used a form of random sine and saw waves similar to a synthesizer whereby the sound becomes especially chaotic and high pitched when there is a signal (Dogane, 2007). Aside from serious technical concerns about whether the signals being read are artifacts or not, to me these choices seemed either not very revealing, not aesthetically pleasing, or both. The piano sounds seemed to anthropomorphise the processes involved far too much; why would plants play piano? Why should they be restricted to equal temperament and midi instruments? Would anyone listen to this as a piano piece in its own right? The randomised synth sound reveals more about the signals in the plants but if it were to be presented as a piece of sound art in its own right, would more effort have gone into the aesthetics of the sound or is the artist relying too much on the novelty of the idea that somehow 'the plants were making the sounds'? My goal was to create work that could stand alone as a piece of sound art even if the listener was completely unaware of the scientific side of the piece, yet should further information be required on the scientific side of the piece, that it be readily available. Of course whether or not I achieved this is an entirely subjective opinion, but it is impossible to be truly objective about your own work, or anyone else's.

6.2 COMBINING SCIENTIFIC DATA AND ARTISTIC LICENSE

In multidisciplinary work which mixes science and art, I would argue that not all sounds necessarily need to be controlled by the data. Otherwise the artist becomes little more than an ornate ECG machine. Even when revealing hidden structures within the natural world that may in themselves be quite beautiful, in my own practice if I am not interacting with and changing the material to a high degree then I am not satisfied I have enough creative influence over the work, thus an element of craft and hard work is also important. It could therefore be argued that some sounds can be used simply because the artist feels inspired to use them in a particular context. Some works, especially ones which use scientific data, seem to me to neglect the aesthetics of the piece (Dogane, 2007), something that perhaps they would be unlikely to create if they were making a purely artistic or musical work. Whilst limitations are sometimes viewed as an advantage in composition I think such limitations should always be ignored if the artist sees that good artistic results can be obtained by doing so. This then means that a work can become a true integration of science and art as opposed to art being reduced to the role of a puppet animated only by strings of data. However here it must be stressed that if the composition uses no data at all or if the data is so mangled that it bears no relation to the original input, then it becomes a purely artistic endeavor, and at this point all claim to it being in any aspect a scientific project should be abandoned. In the case of the installations discussed here, a difficult balance had to be struck; the composition had to be aesthetically pleasing, but it also had to make tangible bioelectrical activity in plants. There is no reason that art and science cannot exist side by side as two aspects of the same piece. One may influence and react to the other but doesn't have to control it completely. In the case of the installations I made for this portfolio, scientific data radically changed elements within the composition but were not always the whole composition. I wanted the artistic side of the work to be free to explore the furthest realms of the imagination, but at the same time the scientific side to be strictly controlled and have a technically robust basis. So whilst I have used sounds that are controlled by the signals and that I find subjectively pleasing, I have also used sounds that fit in with those sounds but are not directly being produced by the signals. In this way the pieces could grow in a way that suited the space they were in and allow solutions to purely compositional artistic problems to be found rather than merely be the sonification of data.

With these installations I seek to do something technically new in the field of plant electrophysiology; I also seeks to do something new artistically, especially in the field of spatial audio. Advancing the field of spatial audio, therefore, also plays a large part in the creative and technical side of this submission.

6.3 COGNITIVE EFFECTS, SITE SPECIFICITY AND AUGMENTED REALITY

I have noticed that an installation can be a lot more effective if audio cues are supported by visual and cognitive ones. This is supported by research that shows that the context in which an object is seen (or heard) massively affects the person's experience of it (Tyléna, 2011). It has also been demonstrated that people often hear what they expect to hear based on visual and cognitive cues (Wallach, 1940). Such cognitive and visual cues can be incorporated into the design of an installation to enhance a sense of believability and can override or enhance spatial audio cues. If a suitable location can be chosen then it can add greatly to the effectiveness and impact of an installation. For example, if a sound installation features a lot of bird noise it is more believable if it takes place on speakers hidden up trees than fully visible speakers on stands in a gallery with white painted walls. Whilst this might not be relevant to recorded music in general, ultimately this gives the installation artist more power to transport the listener to the desired environment. The most convincing lies are after all ones that contain elements of truth. Unlike in theatre, visual props and cues are sometimes not considered in the world of sonic art yet they can greatly enhance the experience. Here, subtly used sound can augment reality by adding to it a thin layer of impossible noise that is nonetheless blended with the world subtly enough to be believable and can thus emulate auditory illusions.

The choice of location, therefore, becomes another tint in the artist's palate, another creative decision and part of the finished art object.

7 SPATIAL AUDIO TECHNIQUES USED IN THE INSTALLATIONS

As previously mentioned site specific spatial and 3D audio form an important part of the creative side of this work. To a large extent these compositions do not work in stereo, or even in multichannel facilities, they only work with very specific speaker configurations, in very specific places and using very subtle cognitive cues.

With regard to listening to stereo, or even quadraphonic versions of multichannel installations, when describing his own work, 'The Shaman Ascending', Truax says:

'*Without the spatialisation of those sounds rotating around it would be impossible to listen to , it would be just be a wall of undifferentiated material..... the space and the sound are completely integrated.*'

(Truax, 2010)

This is certainly true of all the installations described in this thesis, taken out of their visual and cognitive context, the site they were designed for, and listened to on a reduced speaker array for which they were not designed vastly reduces their impact and at best provides an obscure snapshot of the original installation.

As well as the mapping techniques described in this chapter the installations often use non peripheral speaker arrangements and automated trajectories. Many installations have used non peripheral arrays before such as the Phillips Pavilion (Treib, 1996) and hiding speakers, even in trees, is not a new phenomenon either (Allen, 1986). However these different aspects are combined with more modern automation and 3D audio technology and have different objectives especially with regard to spatialisation. They also make use of trajectory panning between miniature arrays and larger arrays and arrays that are close to the listener and far from the listener. These techniques combined effectively solved one of the problems of spatial audio, that of focused sources, and how to get sounds to come close to the listener. By hiding the speakers close to the listener and automating between them the impression was of sounds floating close to the listener's head, without any obvious technical cause. This effectively achieved what wavefield synthesis tries to achieve with focused sources but more effectively and with far less speakers.

For correct speaker configurations, a speaker map is included with each installation multichannel file. During the course of this research several new developments were made in my artistic practice in the field of spatial audio. Often a solution to a scientific or practical problem could be found within the field of spatial audio. The technologies involved in creating multichannel audio and multichannel electrode arrays are also remarkably compatible, with the possibility of matching one audio channel to one electrode channel **(see Fig 7.1)**. This made multichannel spatial audio the ideal artistic technique to complement multichannel plant electrophysiology.

Figure 7.1 An 8 channel DAQ (top) makes the perfect complement to an 8 channel soundcard (below).

When I initially started the PhD one of the things I wished to investigate was how a plant's natural soundscape affected its electrophysiology. Although as already mentioned there is evidence plants respond to sound, claiming that plants can 'hear' is still unsubstantiated, nor is it clear what kind of 'plant related transfer function' (PRTF) would be involved should that be the case. Nonetheless plant electrophysiologists suggested to me that if I ever decided to test sounds from their natural environments on plants the techniques I used should as faithfully represent the authentic soundscape as possible. There are numerous possible reasons for this: there are many qualities of sound apart from frequency, such as the angle of incidence of a sound hitting a plant. On top of this the context in which a sound is made, such as the time of day, temperature, humidity or combination of other noises sounding at the same time, may conceivably give new 'meanings' to plants and whether or not they consider a certain sound as a possible threat or not. Of course all of this is highly speculative however in order to properly assess a plant's reaction to sound all these parameters, and many more, must also be considered. This meant that the spatial characteristics of the sound were also to be considered and led to the development of the, essentially heuristic, technique discussed in this chapter.

Although I conducted some experiments testing plant responses to sound at LINV, it was not ultimately the avenue down which the research progressed; however these spatial audio techniques turned out to be very useful and were used creatively in many of the installations. Further spatial audio techniques that were used are included in individual accounts of the installations. Several installations were conducted to test out the efficacy of these techniques. Although not all these installations were directly related to plant electrophysiology, the spatial audio techniques developed in them contributed to subsequent installations that were. As such they serve as relevant case studies to illustrate the development of the technique which shall be described in detail in this chapter. Aside from possible scientific applications they constitute an important development of the artistic side of the research as well.

The recording techniques described in this chapter constitute an alternative method of recording 3D sound scenes using several separate SD card microphones as opposed to using single multi capsule ambisonic or surround sound microphones. Details are provided on how to set the microphones up, appropriate directivity and positioning, and speaker setup for reproduction. The advantages and limitations of the approach compared to other sound spatialisation techniques the artist has tried, such as wavefield synthesis (WFS) and ambisonics, are discussed. Three sound installations that use the technique are used as case studies to illustrate how to implement it effectively. Although qualitative data and listening tests are not gathered a subjective description of the effectiveness of the spatialisation is given and an account of the public response is also provided.

7.1 A Heuristic alternative to Wavefield Synthesis and Ambisonics

When an artist first decides to branch into multichannel audio and the recording of 3D sound-scenes they are usually presented with two options - Ambisonic microphones or quadraphonic microphones. These usually consist of a single mic placed in a central location which records the sound-scene around it. However, there is an alternative technique which uses multiple microphones. Although it is simple and effective, it is not well represented in the literature probably due to the fact that it has only recently been easy to implement due to the advent of small, portable standalone SD card recorders. Such technology has allowed for new ways to record relatively large areas, for long durations at a relatively low cost, making technology and techniques available to artists that were not previously accessible, or which were prohibitively expensive.

For one installation I wanted to record the 3D soundfield of 10000m^2 of tropical rainforest and reproduce it as identically as possible in a 10000m^2 of tropical botanic garden. I decided to experiment with different approaches to recording dynamic 3D audio scenes due to dissatisfaction with commonly used techniques. Encouraging initial results from this on-going project led to a diverse range of applications which shall be discussed later in this chapter.

7.2 Proximity illusions

One of the main challenges encountered in spatial audio composition is creating 'proximity illusions', or what are known in WFS as 'focused sources'. In laymen's terms this consists of making a sound seem as if it is coming close to the listener. Creating a sense of depth and layering within the listening area, such as the sound of a person walking around a room with accurate localisation, can be problematic as in most multichannel facilities the speakers are lined up around the periphery of the room. Ambisonics and WFS's use of focused sources were not found to be suitable for many site specific applications due to the irregular shape of the spaces involved and the availability of more effective alternatives. One way to describe this recording technique is to say that it is to a distance based amplitude panner (DBAP) what an Ambisonic mic is to a VST Ambisonic panner.

The technique consists of placing many microphones around a sound scene and then placing speakers in exactly the same relative positions that the microphones were originally in on playback. This is not simply the distribution of point sources around a room but seeks to fulfill the same function as an Ambisonic mic in that it is capable of recording dynamic moving sound scenes in 3D spaces with the added dimension of full proximity. Though it requires its own fairly precise irregular speaker placement, it does not require the same degree of accuracy of speaker placement and calibration as other techniques such as WFS and Ambisonics. However, due to its irregular speaker arrays which will change from installation to installation, it has little application in bringing audio into people's homes or cinemas. Where it does prove very useful is in sound installation, theatre and any site specific event especially where it is not easy to implement precise peripheral speaker arrays such as the ones required by Ambisonics and WFS and where convincing proximity illusions are desirable.

7.3 3D AUDIO MAPPING

This technique, which was developed through trial and error, is one which I found to be more effective at recreating 3D sound scenes than other 3D sound recording techniques such as Ambisonics which have trouble getting sounds to appear 'close' to the listener. Having lived in the rainforest for several years, I had a fairly good idea of how it should sound and this technique provided what I consider the most authentic spatialisation for rainforest sounds. No technique can truly match the thousands of thousands of point sources found in a rainforest, but this technique, combined with choosing the correct setting, created a kind of 'cognitive interpolation' whereby visual and cognitive cues combined with the sound to create a more convincing illusion. It also allows for relatively large recorded areas to be scaled down or *miniaturised* which shall be described in more detail in the chapter 'Garden of Membranes'. These 3D sound scenes have several uses. Firstly, they can be used to test how a plant responds to its native soundscape (being the closest artificial recreation of the authentic sound field I am aware of using current technology). It also creates 3D audio documents; such documents may act as indicators of the current state of rainforest biodiversity as well as being documents for future generations to hear how the rainforest actually sounded in the past in a more authentic way than traditional recordings can provide. The recording and reproduction techniques used represent a significant improvement on traditional techniques such as Ambisonics which similar projects are currently using such as 'Fragments of Extinction' (Monacchi, 2011). Finally, such 3D recordings can be altered creatively to make unusual collages made from original recordings that would not be found naturally.

7.3.1 **Case Study one: Jatun Sacha**

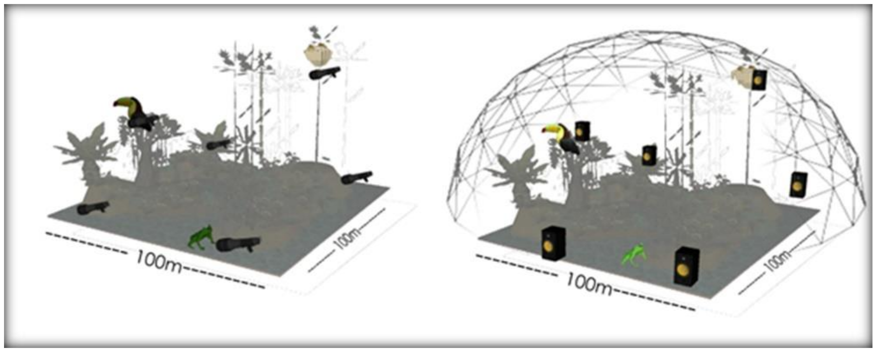

Figure 7.2 3D audio recording and reproduction

In this installation SD card standalone microphones were placed in specific locations over various sized areas of rainforest at Jatun Sacha nature reserve and several other locations for a 24 hour period. The areas recorded ranged in size from several Km^2 to several m^2. Speakers were then placed in several of the installations (Bosque Encantado, Surrounded, Garden of Membranes 2.00) in the same relative positions that the microphones were placed originally in the rainforest (**fig. 7.2**) (**see video '3D audio mapping' under Technical> Spatial audio in the attached offline website**). Whilst there were sounds in the installations that were controlled by electrical signals, the 'sonic maps' constitute an important element of the artistic side of the research and the perfect 'sonic chassis' in which dynamic sonic elements of the installation, that were being controlled by plant signaling, could be contained. One aspect that I personally found fascinating about this is that I knew that I was walking inside a 3D sonic document that essentially was a sonic map of several kilometre squared of rainforest reduced into a much smaller space, recordings from microphones that had been half an hour's walk from each other during recording could be reached by merely crossing the room. Even more fascinating was when this sonic map was further miniaturised into 1m squared of Bonsai forest, using several miniature speakers in the forest, a sonic map or a huge area around which the listener could walk. It may be pointed out here that microphones spaced so far apart are unlikely to maintain any kind of cohesive panning relationships between moving objects in such a huge recorded area. However, many different sizes of recorded areas were experimented with, and the optimum distance for maintaining panning laws (e.g. reproducing the sound of a bird flying from tree to tree) is an ongoing area of investigation. It was found that smaller recorded areas allowed for improved panning of dynamic recorded sound objects such as birds flying around.

This is an example of an artistic idea that was inspired by a scientific consideration mentioned earlier in this chapter. As such it fulfills my original remit of finding ways for science to advance art as well as vice versa.

The technique was the culmination of much trial and error. Two other case studies are now presented that, although they are not presented as part of the portfolio as they did not accompany plant electrophysiological sounds, they nonetheless played an important role in the development the technique.

7.4 CASE STUDY 2: ULSTER AMERICAN FOLK PARK

A sound installation at the Ulster American Folk Park in Omagh, Northern Ireland, provided an opportunity to experiment with this method. For this installation, the desired effect was of a Presbyterian meeting house (1850s) filling up with people followed by the congregation taking to their seats and conversing a while before a pastor walks up the steps of the pulpit and begins his sermon. Another element of the installation plays with the 'cocktail party effect' so that the listener could hear either the murmur of the room, or sit beside an individual conversation and 'eavesdrop', each conversation containing pertinent historical data. This cocktail party effect would later prove useful in the plant electrophysiology installations, but human conversations would be replaced by the sounds generated by plants.

7.4.1 **Microphone and speaker placement and type**

Eight microphones and eight speakers were used (**Fig. 7.3**) and the speakers were placed in the same positions as the microphones were originally. In general, the microphones should not be placed in a grid or any regular type of configuration; instead they should be placed nearest to the most important sound sources in the scene. In this case they were placed at the entrance of the door (to capture people's footsteps as they walked in), at the pulpit (to capture the sound of the pastor walking up the steps and beginning his sermon) and then in six separate pews (to capture the sounds of people filling the spaces, sitting down and conversing).

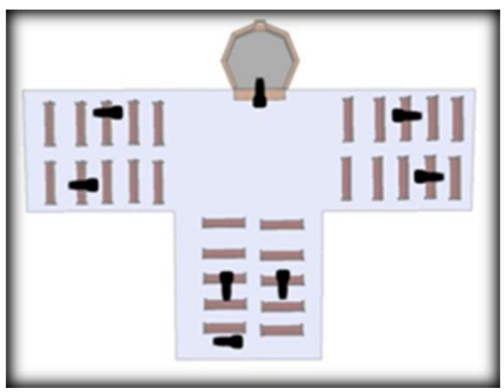

Figure 7.3 A top view of microphone placement in a church amongst the pews and pulpit. Speakers subsequently occupied the same positions

7.4.2 Synchronisation

SD card microphones can be synced by placing all of them on a table, pressing record on each one and then clapping before deploying them round the sound scene. These recordings can later be easily lined up later in a DAW.

A test in which a second clap was made at the end of the recording showed that after 50 minutes on some recordings a slight desynchronisation between some machines occurred. This drift never exceeded three milliseconds. This desynchronisation is unlikely to cause noticeable problems unless very long recordings are made and does not occur at all on shorter recordings (e.g. less than ten minutes). The degree to which this error occurs is likely to vary from machine to machine and it is advisable to test recording devices to see how long you can record for before audible desynchronisation occurs.

7.4.3 The panning law is defined by the directivity of the microphones and speakers

In general the directivity patterns of the microphone should be matched to the dispersion pattern of the speakers being used, though this should also be adjusted to reduce bleed through from other areas of the room. For example, when people enter the room it is undesirable for the microphone by the pulpit to pick up the sound of people entering the church by the door, because when the recording is played back it is undesirable for the sound of the people entering the church to come from the pulpit, only the entrance. Care must be taken that the microphone has the correct directivity and as much as possible only records the sounds in its immediate vicinity. One solution is to use a fairly directional microphone dangling from the ceiling pointing downwards two or three metres above the ground (**fig. 7.4**). In this diagram the microphones are spaced in a regular pattern; this would not be the case in most situations. The same principle could be applied by pointing microphones upwards or in various different directions depending on the peculiarities of the sound scene to be recorded.

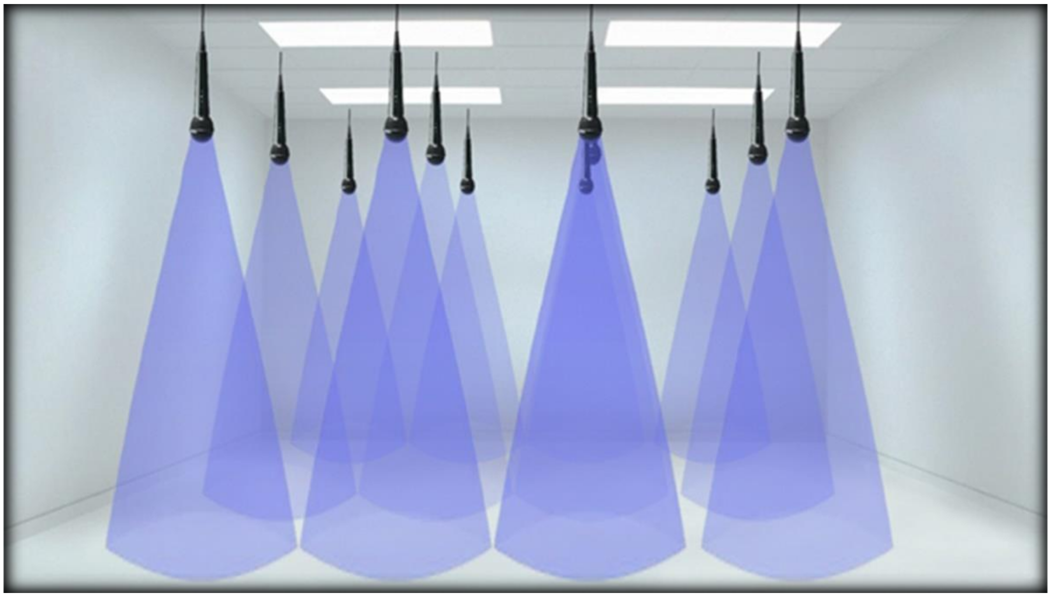

Figure 7.4 With careful consideration of microphone directivity and placement, interlocking 'soundpools' can be recorded by pointing microphones downwards and only recording what is immediately below them, thus reducing bleed through from other areas of the room

Inevitably there will be some bleed through from other areas of the room due to room reflections and imperfections in microphone directivity patterns. Conversely, if microphone directivity is reduced too much, panning information will be lost as there will be a 'hole' between the two pools of sound where neither microphone has picked up; so it is a balancing act between reducing bleed through and retaining the approach of moving sound elements to recreate natural panning. Experimenting with different microphones, microphone placement, speakers and directivity could help to further improve the technique in future.

7.4.4 **Speaker placement**

Once the recording is made, it is important to make sure that the speakers are placed in exactly the same relative positions as the microphones were in whilst recording, or in the case of a permanent sound installation in a museum, as close as the builders and curator will allow. In this case, the speakers were placed just out of sight under the pew in front of the original microphone position, approximately twelve inches from their original position. This did not overly distort the spatialisation. Generally they should also be placed in such a way so that the driver emits sound in the opposite direction to which the microphone received the sound, though this is not always strictly necessary.

7.5 CASE STUDY 3: GRAND OPERA HOUSE 2013

Another sound installation involved a theatre production at the Grand Opera House in Belfast. A steam train was recorded using this technique by placing microphones around a train track, and then, by placing speakers under the audience's seats and above them in a similar configuration to the microphones, the effect of a steam train passing directly through the audience was achieved. The effect was made all the more convincing by the vibrations of the seats caused by the speakers. Again cognitive effects were used to enhance this illusion. It is hard to get the audience to imagine that a steam train is passing through them when they can't see one, so the effect was further enhanced by listening to it in total darkness.

7.6 ENHANCING THE RECORDINGS IN THE STUDIO

Some of the bleed through from microphones may record unwanted sounds, such as the above example of the pulpit recording very faint sounds of people entering the church, despite attempts to adjust directivity. These can be simply faded out in your DAW at key moments in the soundscape such as when people are entering the room, though it will be impossible to remove them entirely.

7.7 PREVIOUS USE OF THE TECHNIQUE

Despite an extensive and on-going search, almost no literature on this technique has been found by the author to date. This is likely due to developments in technology which have made the technique easier to implement. However, there are some earlier developments and related techniques. The first was Harvey Fletcher's 'Curtain of Sound' in the 1930's which sought to reproduce the sound of an orchestra by recording using a curtain of microphones whereby one microphone was reproduced by one speaker, the result being 2D rather than 3D (see **fig. 7.5)**.

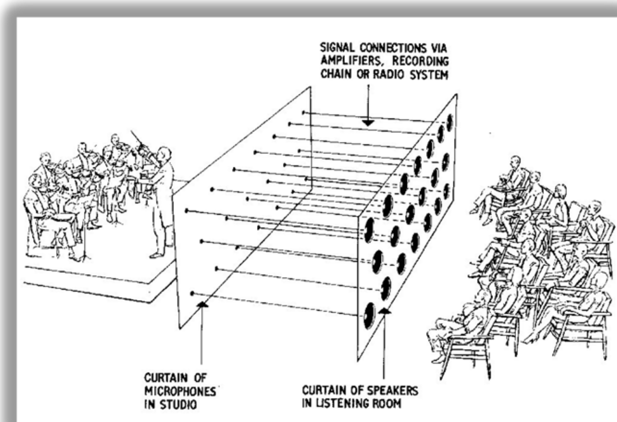

Figure 7.5 Harvey Fletcher's 'Curtain of Sound'

A similar more recent example is Erwin Roebrook's 2011 'Sonic Window' (RoeBrook, 2011) in which he placed many microphones in a two dimensional square array to record a 'window'. Speakers were then placed in the same place on playback to reproduce the same sound window. In the current case this 2D sound field is being extended into three dimensions and dispensing with the grid-like array as well as eliminating microphones from where there are less significant sound events. Another related work is Gilbert Briggs' 'Live Vs Recorded' demonstrations in the 1950s, whereby he recorded four instruments and subsequently played them back with the speakers in the same places as the players had been sitting (Gearplus, 2007) (see **fig. 7.6).**

Figure 7.6 Gilbert Briggs 'Live Vs Recorded'

This, of course, was not a dynamic moving 3D sound scene, but rather four static point sources. The most similar technique used was by sound artist Jean-Marc Duchenne who replied to an email from the author;

'I actually work on some recordings using a similar technique,… ….I try to keep most of the original spaces, while making them overlap between each other. The recordings are 10 channels, in different spatial and microphones arrangements, and the diffusion will be 16 or 18 channels.'

(Duchenne, 2013)

This technique, although similar, differs in its use of diffusion. In the case of the current technique, the amount of playback channels/speakers and microphones must correspond precisely, in both quantity and location, or the effect is lost.

7.8 Results

The soundscape in the meeting house portrays people walking into the building, congregating and taking their seats next to you. Members of the public expressed bewilderment and even fear as if the meeting house was filling with ghosts. As the speakers are placed irregularly throughout the space, the sensation of layers of sound and of closeness and distance is present. The listener can walk around some speakers and sit on the outside or the inside of parts of the array. As a result, there is no 'sweet spot'. The panning relationships are reasonably well preserved; you can hear people walk to distant parts of the room and then sit down, and then you can go and sit down and eavesdrop on their conversation.

For this installation, as most of the recordings were created in the reproduction space, the sounds recorded on-location have a slightly more convincing aspect than if they had been recorded elsewhere, such as in a studio. The sound of feet on the concrete floor is on exactly the correct concrete floor, so the sound is appropriate. The sound of the pews being slammed shut actually is the sound that those very same pews make when a member of the public slams them shut. The sound of the pastor walking up the steps is the sound of someone walking on those exact steps. In this way the sound installation is, although perhaps subtly, more convincing to the audience.

The train effects in the Opera House installation, although played back in a different location, proved extremely effective in showing that to some extent the technique is transferrable as long as the original speaker configuration can be preserved. The effect was no doubt also enhanced due to the fact it was listened to in complete darkness. Public response and reviews were positive.

'….sound to great effect in this show. Using surround sound technology, trains rattle through the theatre, making the audience feel very much like they're right in the middle of the action.' (Rawe, 2013)

'The audio soundscape is wonderfully evocative. The sound of steam trains rumble through the theatre.'

(Meredith, 2013)

7.9 DISCUSSION OF ADVANTAGES AND DISADVANTAGES

One disadvantage is that room reverb will be doubled - once on the original recording, and again on playback in the space. However, as long as the reverb is not too long, it is not particularly noticeable. There will always be some bleed through from other areas of the room onto all microphones, however despite this the author found it the most suitable technique for use in site-specific applications.

Another limitation is that the 3D sound field may be tailored to match the acoustics and environment of a specific space, meaning that it may not be easy to reproduce the results anywhere else unless the environment closely matches the original space. This is also an advantage however, in that it will match the space perfectly for which it is designed. For this same reason, whereas elements such as narrative might be better recorded in the studio, any final mixing should be done in the space itself and not in the studio.

Reproduction, however, need not be restricted to exactly the same space in all cases. Obviously in the case of a church it would be extremely difficult to convincingly reproduce sounds elsewhere without building another church with the same features. However, as the example of the steam train in the theatre demonstrates, it is possible to recreate the illusions elsewhere in some cases. Potentially conflicting visual cues can also be eliminated by listening to certain elements of installations in darkness. If another environment is reasonably similar, such as a tropical forest sound field transferred to a tropical botanic garden, as long as the speaker positions are maintained, reproduction should still be effective.

Another disadvantage is that if it is desired that a sound is to come close to the listener, a speaker has to be placed close to that listener. This presents obvious practical and aesthetic problems in open spaces, especially if it is desirable that the speakers are hidden.

The main advantage is that it creates a much more authentic representation of the original 3D sound field than other techniques I have used or heard especially with regards to height and proximity. Since publication the technique has been used by other composers at the ISSTA 2016 'International Festival and Conference on Sound in the Arts, Science & Technology' reportedly to good effect (Bates, 2016) .

This technique was later used in several installations that directly integrated with plant electrophysiology and shall be described later.

8 INSTALLATION: 'INVISIBLE FOREST' TEMPERATE VERSION

'Invisible Forest' took place at the Sunflower Festival, Northern Ireland in August 2013, and was billed as 'an immersive 3D sound installation that allows both the plants and the listener to participate in the soundscape'. The installation ran for three days.

A video 'Invisible Forest' documents the sound installation (Leudar, 2014) and can be watched on the accompanying offline website (**Installations > Invisible forest**) and a short mixdown of the installation can be found on the **USB drive > Audio > Invisible Forest >** "**Invisible forest quad.wav**" can be heard in the folder labeled "Invisible Forest" on the flash drive.

By harnessing electrical signals in trees and using them to influence the composition of a multichannel sound installation, this was the first installation to try and make tangible hidden bioelectric activity in plants and also consisted of a first step towards detecting signals traveling between trees possibly across the mycorrhizal network. In addition to this, the goal was to create a spatial audio composition that stands as a piece of art in its own right, whether or not the listener is aware of the scientific background of the piece. The installation was created before audio mapping techniques were used, but still used spatial audio techniques.

8.1 TECHNICAL DETAILS, MATERIALS AND METHODS

The sound installation consisted of 16 speakers hidden amongst the trees and undergrowth of the woods. Four of these were larger Mackie SRM 450 and the others were smaller Behringer MS16 speakers. The four large speakers were at ground level and created a quadraphonic sound field across the whole woodland whilst the smaller speakers were placed in a grid of eight in the treetops (**see fig. 8.1**) as well as four additional small ground level speakers being placed next to trees from which electrical signals (action potentials) were being read (**see fig. 8.2**). It also consisted of a computer, a 16 channel sound card, 350m of XLR audio cable and low loss single core shielded electrical cable for the electrodes.

8.2 READING THE ACTION POTENTIALS

Research has shown that trees communicate with each other across the mycorrhizal network (Song et al., 2010). To accurately demonstrate whether action potentials travel across this network was beyond the scope of this installation though it represented the first step towards this goal.

In this installation action potentials from four different trees were measured. The aforementioned op amps were used with the DAQ. As the cables from the electrodes to the computer were long (20m in two cases) low loss shielded single core cable was used.

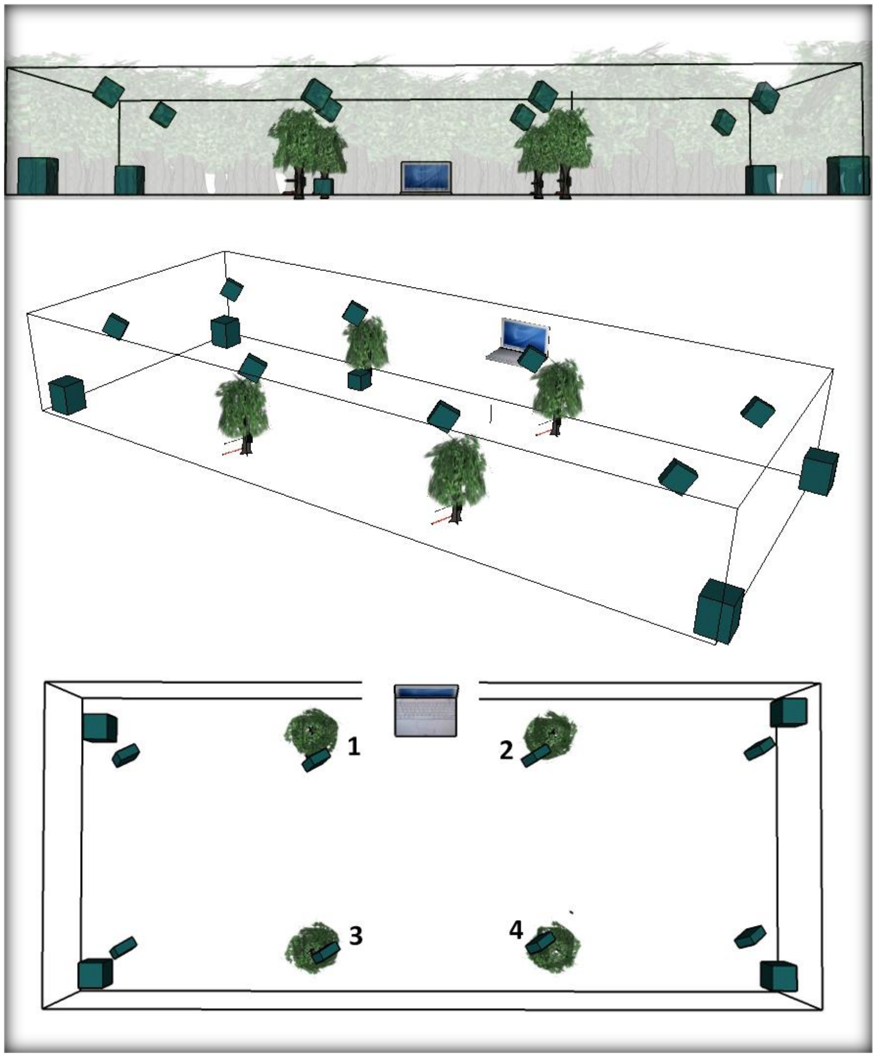

Figure 8.1 Shows four large speakers in each corner and eight smaller ones in the treetops. The numbers 1,2,3,4 in the bottom picture show the presence of electrodes and another speaker for each tree.

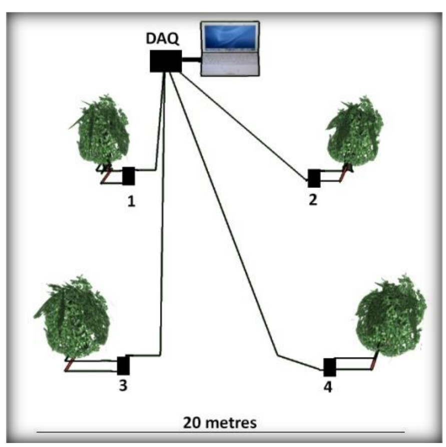

Figure 8.2 Positioning of op amps and electrodes, one for each of four trees

8.3 APPLICATION OF THE ELECTRODES

A small hole was made in the tree for each electrode. Holes were kept as small as possible to minimize trauma but it was important that the electrode penetrated the fleshy inner layer of the tree (the phloem). Graphite electrodes were used, and the conductivity of these can be further enhanced by using ECG gel which also helps minimize trauma. The electrodes were allowed to rest for several hours after being inserted as wounding potentials may take a while to subside. Both reference and the working electrode were placed in the trunk of the same tree and the op amp unit was placed close to the electrodes. Both were put out of reach of people to prevent tampering with and electrical interference from the public. They were also kept well away from electrical cabling.

Cables from the op amp units went back to the DAQ and from the DAQ to the computer (**fig. 8.2**). Once in Max MSP, a threshold was set at around 60mv (the background noise was around 20mv). If an action potential caused a spike above 60mv then a sound would be triggered. This threshold was adjustable in case background noise or the strength of potentials changed significantly due to light levels, temperature or moisture. Each channel of the DAQ corresponded to a particular tree and also a particular audio channel (**fig. 8.3**). These channels delivered audio to the speaker next to the tree in which the electrical signal had originally been generated. So channel 1 on the DAQ corresponded to channel 1 on the sound card, channel 2 on the DAQ to channel 2 on the soundcard and so on.

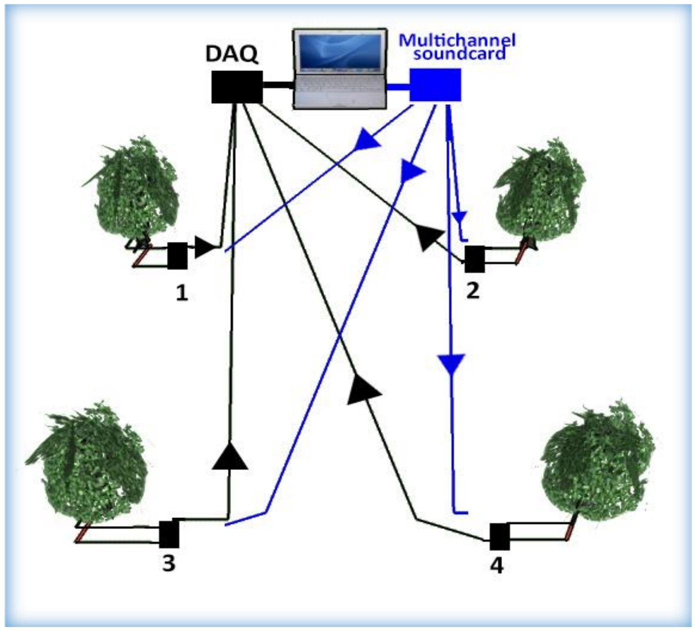

Figure 8.3 Electrical signals enter the DAQ (black lines) from the tree and are converted into audio in Max/Msp and are then sent back to a speaker next to the tree which put out the original signal (blue lines).

8.4 THE COMPOSITION

Ideally, I try to create site specific sound installations that are tailored to the environment in which they will be reproduced. For this composition ancient deciduous woodland would have been ideal, but was not available so the installation took place in young deciduous woodland. This woodland consisted of Birch *Betula pendula*, Beech *Fagus sylvatica* and Oak, *Quercus robur*. Due to the aforementioned cognitive factors I kept speakers hidden to help create a more convincing illusion. The context in which this sound installation was presented was also important: if the listener is not aware they have entered a sound installation, or if sounds can be presented in a more believable context as if they might just be part of the real environment and not part of a 'performance', the audience response can be markedly different. In this case most of the soundscape was composed at the site itself, resulting in the installation being perfectly tuned to the acoustics of the space.

There were three elements to the composition. The first was the sounds triggered by the electrodes, the second was the soundscape which was present in the wider sound field, which interacted with these electrode-induced sounds, and the third was hidden microphones which allowed the public to interact with the soundscape and the sounds coming from the trees.

Various different sounds were triggered by the trees. Two programs were used to process sounds. Max MSP contained the electrode software and would trigger sounds when signals were present and these sounds would subsequently be routed into a DAW where they were spatialised and processed. Some were bell-like sounds which when triggered in any order would form a kind of tune or harmony. These sounds were slightly time stretched at the end and faded out with descending and ascending artifacts to allow them to 'blend' and harmonise with each other. The other sounds used were time stretched and pitch shifted bird songs. When slowed down, elements of bird song can be particularly eerie and primordial, suitable for the woods at night. As the sounds which were coming from the trees that produced the signals covered a wide range of space, sounds seem to come from many different places in the darkness of the forest, creating a sense of depth.

8.5 THE WIDER SOUNDSCAPE

The four trees formed a cube in the centre of the sound installation. Interacting with and surrounding this cube was a wider soundscape (**see fig. 8.5**). The wider composition was designed to integrate fluidly with the sounds produced by the trees and vice versa. The sounds used by the trees informed the wider soundscape that was built around them but the sounds that were used by the electrodes were in turn altered to fit the soundscape. These sounds changed over time according to my whims. This is a kind ongoing process similar to automatic writing whereby the soundscape (once initial parameters and sounds were set in motion) begins to evolve by itself, with the artist adopting almost a problem solving role in order to resolve the composition. As such the installation had a live element to it and sounded considerably different at the end of the three days than it did at the beginning. The sounds used changed according to the time of day both due to the activity of the trees and the artist's deliberate manipulation.

8.6 SPATIALISATION

Spatialisation was an integral part of the composition. As the speakers were not surrounding the periphery of the listening area but rather spaced out within it, albeit mostly above the listeners, a convincing sense of depth could be achieved when panning sounds across them (**see figs. 8.5 and 8.6**). This used a similar technique to DBAP (Lossius, 2009) and was more effective at creating illusions of proximity than my previous experiments with wavefield synthesis. The spatialisation was tailor-made for the environment and would be difficult to replicate elsewhere. In reality, it would be necessary to remix it for a different space. Unusual sounds such as flocks of bizarre birds were able to fly from tree to tree and blend with the sounds produced by the electrodes. Sounds were also able to travel downwards from the trees to speakers at ground level. Some of the panning relationships between the speakers are shown in **figs 8.4 and 8.5.**

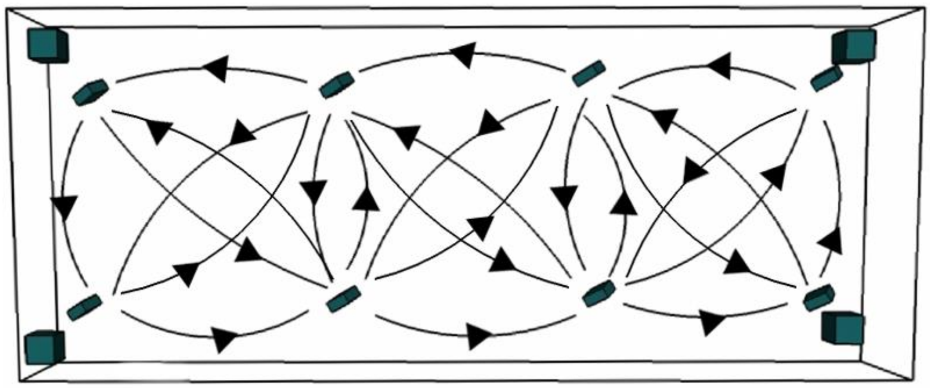

Figure 8.4 View from above the forest (diagram covers approx. 1 acre). Some of the horizontal trajectories' sounds could take through the treetops above the listener.

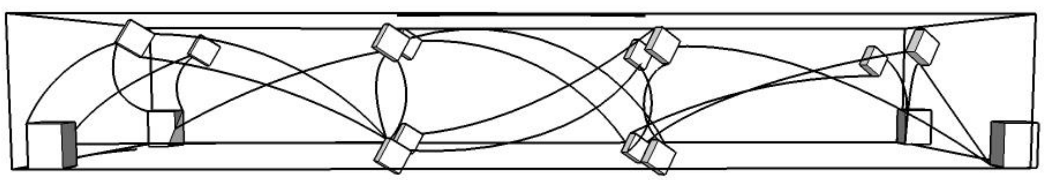

Figure 8.5 A side view of some of the panning relationships used in the vertical and horizontal plane.

8.7 MICROPHONES

Both artists and members of the public were curious as to whether their instruments or voices would be able to affect the electrical signals in the trees. They also wished to participate in the composition of the soundscape. This was made possible in two ways. Firstly, artificially created flowers in the centre of the installation contained microphones in the stamen. The voice of the person singing into the flower was modified and restricted in such a way as to fit in aesthetically with rest of the soundscape. The voices were also spatialised amongst the trees in a way that allowed the voice to travel around the treetops. Instrumentalists (e.g. violinists and flautists) were able to wear radio mics and as they moved around the forest the effects on their instrument would follow them. Instrumentalists were particularly keen on interacting with the sounds produced by the trees.

Although the aim of this installation was not to gather quantifiable data on whether or not bio electrical activity in the trees change in response to certain sounds or frequencies, a casual observation indicated that no such response was present.

8.8 PUBLIC RESPONSE

Although the objective of these projects was not to gather qualitative data, the public response can be a useful indicator for an artist with regard as to whether the intended effect of the work matches the audience response. In this case the public response appeared favorable, appealing to a wide demographic from children to adults, and visiting sound artists from both Belfast and Europe expressed enthusiasm for the project. Approximately 2000 people in total experienced the installation. Three elements of the installation captured people's imagination. Firstly, the idea that trees could communicate with each other via an underground network and the idea that electrical signals in the trees had been made tangible. Secondly, people playing instruments and singing into the flowers were enchanted by the idea that they could interact creatively with the sounds being produced by the trees. Thirdly, the spatialisation of the installation surprised people; many members of the public were unaware that there were speakers hidden in the vegetation, and this enhanced the sonic illusion and created a particularly vivid effect on people. Those who spoke into the microphone to hear their voice creep back through the treetops towards them in a substantially altered form were unable to work out how their voice had become 'externalised' and returned to them, in the absence of any visible technology. This seemed like a form of magic trick that they couldn't fathom. Those who were more familiar with sound installation or who had guessed that there were speakers hidden in the trees focused on different elements of the installation such as how the sounds matched the environment and interacted with each other. This elucidates how cognitive visual factors can be used as a tool to affect audience response. Whilst some children enjoyed shouting into the microphone flowers, when dusk settled some of the more creatively inclined adults constructed improvised and subtle soundscapes upon the sound emitted by the trees and soundscape, some of which were recorded. The sound installation was the subject of two interviews, part of which was shown on the BBC2 Arts Show and the other for a local arts blog. **Coverage along with a video explaining the installation can be seen in the offline website 'Installations > Invisible Forest'**

8.9 REFLECTION: WHAT DID AND DIDN'T WORK?

Although the electrical signals in plants were read as accurately as possible, and sounds were triggered by these signals, I am not convinced that this demonstrated any form of communication between the trees. To do this, far more electrodes would need to be used and it would be necessary to insure that they were placed in the same channels, in other words that they were placed along routes along which signals travelled between trees.

Nonetheless, it proved an interesting first step towards sonifying electrical signals in the forest and is the first time anyone has attempted to do so.

9 INSTALLATION: GARDEN OF MEMBRANES 1.0

'*Garden of Membranes*' is part sound art installation, part living sculpture and part scientific research project. It realizes several innovative scientific and artistic ideas.

The installation was exhibited at the Clandestino Festival of Contemporary Art in Bolivia in 2014 and a more developed version at the Naughton Gallery in Belfast, Northern Ireland in 2015 which shall be described later. The installation ran for 12 hours a day for one week. *Garden of Membranes* detected electrical signals in a miniature forest consisting mainly of *Crassula ovata*. A video of the installation can be seen with accompanying audio in the offline website **(Installations and compositions > Garden of Membranes 1.0.).** An audio excerpt can be heard on the **USB drive> Audio > Garden of Membranes 1> Garden of Membranes quad.wav**

9.1 THE SCIENTIFIC PART OF THE INSTALLATION.

One of the main obstacles to performing research on electrical signals in a forest is that difficult environmental conditions present technical difficulties, such as rain shorting out electrodes. As well as this, it is very difficult to know for certain if the roots of the trees are connected at all without digging up them up. 'Garden of Membranes' therefore aimed to overcome these difficulties by growing a miniature bespoke ecosystem to predefined specifications. A forest of such a small scale allows any electrical signaling across this network to become evident, allowing for much easier control of environmental factors, such as temperature, light, sound and humidity and would present a far more convenient way to gather data if desired. At the same time it maintains a far more 'natural' ecosystem than those usually found in laboratories.

9.2 THE ARTISTIC SIDE OF THE PROJECT

Artistically its aim is to create a standalone sonic sculpture as well as an immersive and unusual sonic environment using unconventional spatialisation techniques and sounds.

The spatialisation used was, as far as I am aware, the first to use a tiny multichannel speaker array, certainly in this kind of context. Speakers less than one inch in size were hidden around a small Bonsai forest on a plinth in the middle of the room **(fig 9.1).**

The sounds of miniature birds flew around the bonsai canopy and the sounds of tiny animals crawled through the forest. The field recordings used in the installation began where 'Invisible Forest' left off. The piece starts with the sounds of birds found in temperate climates fading into the sounds of the tropical birds and animals of the new environment in which I found myself working. This symbolised the journey that my work was taking across two different continents and in two very different ecosystems.

Figure 9.1 On the left a miniature forest on a plinth on the right the hidden speakers within.

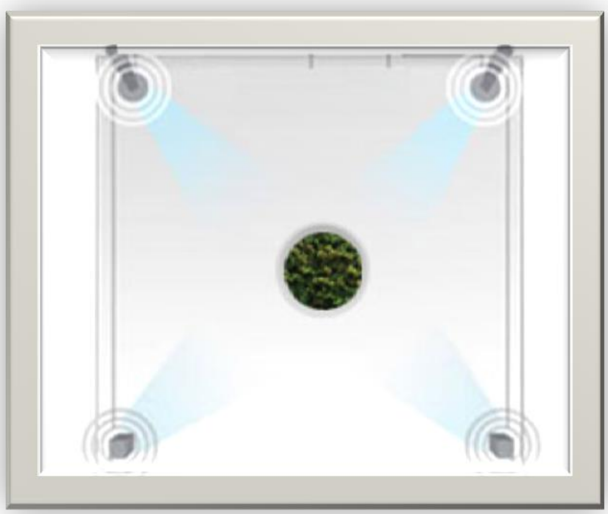

Figure 9.2 larger speakers in the corners of the room interact with the miniature soundscape in the middle of the room.

Figure 9.3 Sounds from miniature speakers in the Bonsai forest panned into larger speakers around the room creating a fountain-like effect.

The sounds were triggered by signals in the electrodes next to individual Bonsai trees. These sounds initiated at their correspondent tree but then the sound welled up from the tiny speakers in the forest and then spread out in to the larger space, emulating a kind of sonic fountain **(fig. 9.3)**. The sounds triggered by the electrical signals resembled the curves of the action potential but were only triggered when the signal passed a certain threshold (usually around 100 mv). The spatialisation consisted of a complex interplay between microcosm (the miniature speakers in the Bonsai forest) and macrocosm (the larger speakers hidden around the room). For example, miniature sounds in the forest might fly to the corners of the room, thereby immersing the listeners. One example was of a tiny bird singing from the branches of one of the Bonsai trees. Panning was used to get this bird to flutter from this tiny tree to a larger speaker in a bush next to the listener's head, appearing to increase in size from tiny to huge. A similar effect was used in the composition at the Eden Project but on a much larger scale. This interplay between tiny sounds which you could walk around, transforming into larger sounds immersing the entire space, played with the listener's sense of proportion and perspective. As with some other installations a sonic chassis using natural sounds was used. The sounds of a miniature rainforest in the Bonsais suddenly expanding and enveloping the listener were particularly effective.

9.3 MINIATURE MULTICHANNEL INSTALLATIONS

It is also the first installation I am aware of which attempts a miniature Ambisonics array and which creates an interplay effect between miniature and larger speaker arrays. I attempted a pyramid array of four miniature loudspeakers using Ambisonics to explore the idea that it might have an interesting effect for listeners walking around the outside of the array as opposed to within in. Initial results were interesting but I feel more experimentation is needed with higher order Ambisonics and more speakers to truly get an idea how well this technique would work.

Eventually I abandoned Ambisonics in favour of normal amplitude panning. By adjusting the panning law I was able to create relatively effective movement of sound objects between tiny and larger loudspeakers.

10 INSTALLATIONS: THE CODE/MYCORRHIZAL MELTDOWN, BOSQUE ENCANTADO AND SURROUNDED; A 3D AUDIO TRYPTYCH

10.1 INTRODUCTION TO THE THREE INSTALLATIONS

‘Surrounded’ 2014, ‘The Code/Mycorrhizal Meltdown’ 2014 and ‘El Bosque Encantado’ 2014 were a triptych of site specific multichannel 3D sound installations which took place in three separate wooded locations: the Botanic Garden in La Paz, Bolivia, the 4th Computer Art Congress in Rio de Janeiro, and the Botanic Garden of Quito, Ecuador. A video explaining ‘Bosque Encantado’ can be seen in the offline website **(installations > Bosque Encantado)** and the software is explained in more detail in the section ‘Software’. A 48 channel version all three was exhibited at the Sonic Arts Research Centre in Belfast in March 2015. A mixdown of this can be found in the accompanying USB stick in the folder **(USB drive> Audio > surrounded > Surrounded Quad.wav).** Live 10 channel Files are also available in **USB drive> Audio > surrounded >10 channel files.**

They represented a considerable leap forward both creatively and scientifically from ‘Invisible Forest’. They used more electrodes giving the network sensor readings a higher resolution, and used far more sophisticated and malleable software, which created soundscapes that continually evolved and did not repeat themselves on a loop. The sounds used were also far more varied and sophisticated and the electrical signals in the plants could affect the sounds in many more ways.

These installations were very much influenced by the culture and folklore of the Amazon region. As research in the area continued to flourish with articles such as 'Root Intelligence: plants can think, feel and learn' (Ananthaswamy, 2014) making the front page of the New Scientist, the idea of an intelligent forest was becoming more acceptable and some of the local beliefs of the Amazonian population, such as that the forest itself is aware, seemed less far-fetched, and it was these ideas I wanted to explore. Our consciousness, or at least our thoughts, from the most reductionist viewpoint could be described as electrical activity in the brain. As complex electrical activity has also been discovered in the roots of trees and the fungal mycelium that connect these roots (Berbara R, 2006), I decided to continue working with the view of the forest as one integrated network .

As mentioned previously, there is firm evidence to suggest that there is communication across this network (Song, 2010), though it is not known if it is chemical, electrical, both or other. In terms of complexity a forest network is many times more complex than the human brain. It is therefore conceivable that the forest itself as a whole could be a form of sentient life, and at the very least it must be acknowledged that it is a hugely complex signaling system. Indeed some of the most prominent scientists in the field believe that plant roots could indeed act as neurons and are 'brainlike' (Baluška, 2004). In reference to these installations however, the goal is not to prove that the forest is 'conscious', especially considering that we can barely define the basis of consciousness in humans. So the goal is simply to make these bio-electric processes tangible, incorporate them into works of art, and allow people to draw their own conclusions.

Just as these installations built on 'Invisible forest', both creatively and scientifically, each developed from the installation preceding it. The work produced is not a series of radically different electroacoustic compositions, but rather the evolution of one large, detailed piece, whose subtle progressions belie many hours of reflection and subsequent programming. Artistically, the prerecorded multichannel chassis or loop was used in 'Surrounded' and it was the first installation to use recordings from several km^2 of rainforest reduced in size. Field recordings were not used 'El Bosque Encantado', 'Surrounded' and 'Mycorrhizal Meltdown'. These were entirely self-generating and did not repeat, at least not in the same way a static piece would, though the same sample may be triggered at a different pitch or place in time. 'Surrounded' did use a prerecorded chassis with the self-generating software and signals in the plants active within it, essentially bringing together two separate strands of research.

10.2 LOCATION

'El Bosque Encantado' and 'Surrounded' were composed in virgin rainforest at a biological research centre at Jatun Sacha. 'The Code' was composed at Omaere reserve in Puyo. Both of these locations were in the Ecuadorian Amazon.

10.2.1 **Jatun Sacha (Kichwa: 'Great Forest')**

Virgin rainforest can be found less than ten metres from the front door of the research centre and botanic garden at Jatun Sacha, and a 100 metre long electrical cable was stretched to a garden of medicinal plants where composition took place in a temporary open air multichannel studio protected by a mosquito net and waterproof plastic (**fig. 10.1**). Initially, I composed the installations at night in the forest, though due to the effect of *playback* described later this shifted towards the day.

Figure 10.1 Open air twelve channel studio connected to speakers over an area of approximately two acres.

Once the composition was complete, for 'Bosque Encantado' it was transplanted to the site of the exhibition in Quito where the same speaker configuration, both in terms of size and position, was replicated. There, fine adjustments were made to the installation to tune it to the particular acoustics of the space. The installations were a combination of several disparate elements which shall now be discussed.

10.3 ULTRASONIC FOREST

As previously mentioned the sounds used to convert electrical signals constitute an artistic decision. In this composition the principle choices of sound sources used in this work were discovered by accident whilst staying on an ecological reserve that had lost most of its fauna. Omaere ethno-botanical park, on the edge of Puyo in Ecuador, has done a commendable job of turning many acres of sugarcane plantations back into rainforest, but most of the animals found in primary forest have not yet returned, leaving a lack of material to record there, at least not in the audible frequency range. I usually left an SD card microphone running overnight deep in the forest, a kind of sound trap in the hope of recording unusual sounds. After another disappointing scan of the previous night's spectrogram I decided to examine some of the ultrasonic sounds that were well beyond the range of human hearing. The spectrograms revealed curious shapes which I began to isolate, noise reduce and pitch down (**fig. 10.2**). This process revealed some extremely haunting sounds, and they formed the basis of much of the sound material in the installations. Whilst hearing individual ultrasonic wildlife sounds slowed down may be interesting, and even form the basis of a stereo composition, when surrounded by these sounds in full 3D audio in the forest, the experience has far more impact. These ultrasonic sounds of the rainforest pitched down into the range of human hearing provide an unusual insight into a world normally hidden from us.

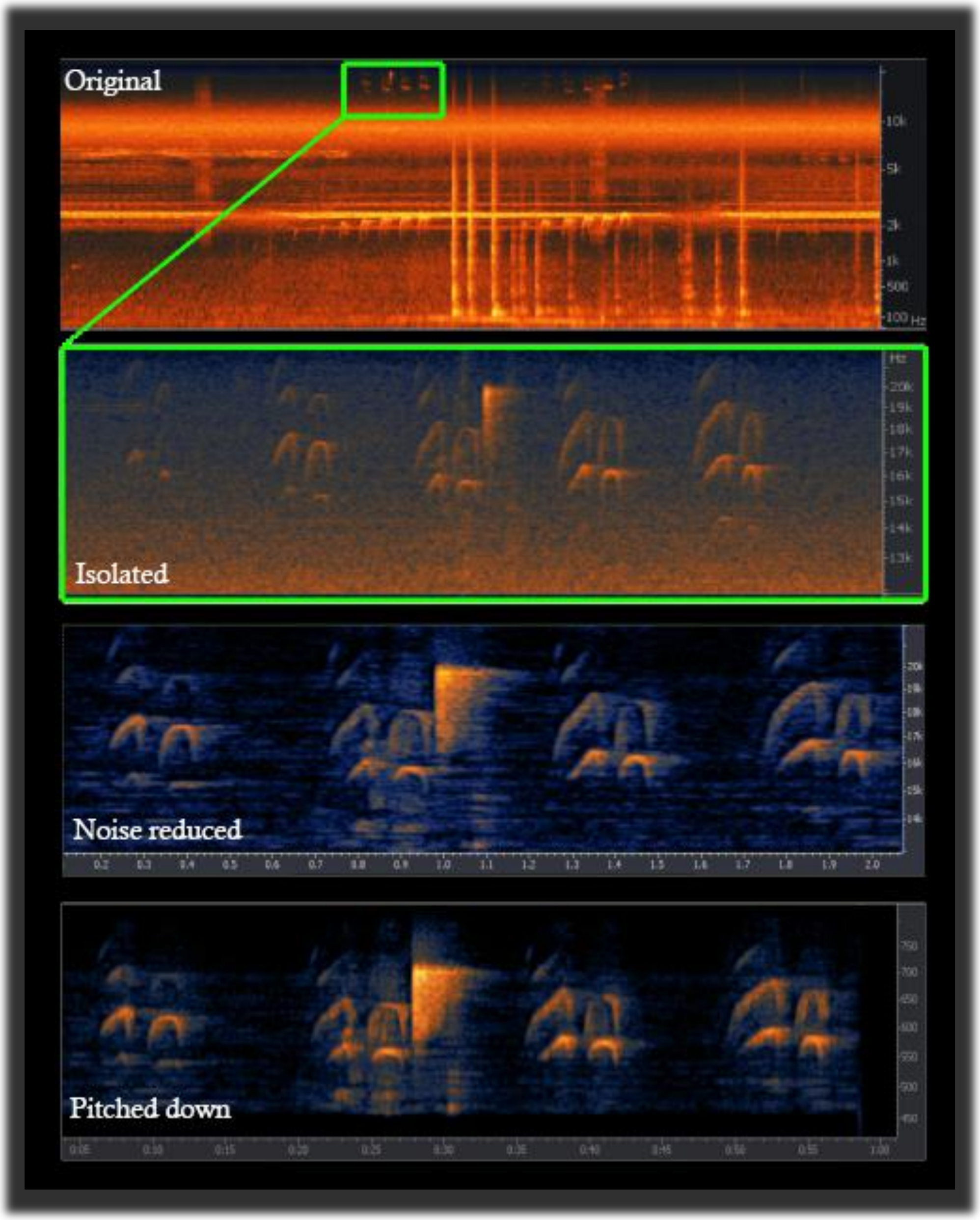

Figure 10.2 The original shows the full spectrogram of the forest and all sounds in it. The sounds selected in the green box and 'isolated' show a sound on the very edge of human hearing and mainly above the hearing of most adult humans (16,000hz). It would certainly have been inaudible in the forest masked by so many other sounds and many people cannot hear it even when isolated. 'Noise reduced' shows the noise reduction process and, if attention is paid to the rulers around the sides of the diagrams, it can be seen that, whilst the shape of the sound is maintained,. 'Pitched down' simply plays it lower and slower. ***Listen to the audio examples above in 'Installations and compositions > Surrounded > second paragraph)' in the accompanying offline website.***

10.4 SPECTRAL COMPOSITION

Spectral composition, like the aforementioned 'sonic sculpture' again has several possible meanings. Here it describes an approach, which although also makes use of spectrograms, is somewhat distinct from 'Spectral Music', a term first coined by Hughes Dufourt in the late 70's (Dufourt, 1979). Eventually it became possible to recognise which sound sources suited the composition merely by looking at the spectrogram. Synthesised sounds with geometric-like shapes and natural sound sources that exhibited complex patterns usually turned out to sound interesting, as well as look interesting. An important visual aspect entered the compositional process. When a section of the installation was bounced down to stereo, it was interesting to see that it exhibited many geometric and graceful forms even when they had been originally picked by ear (**fig. 10.3).**

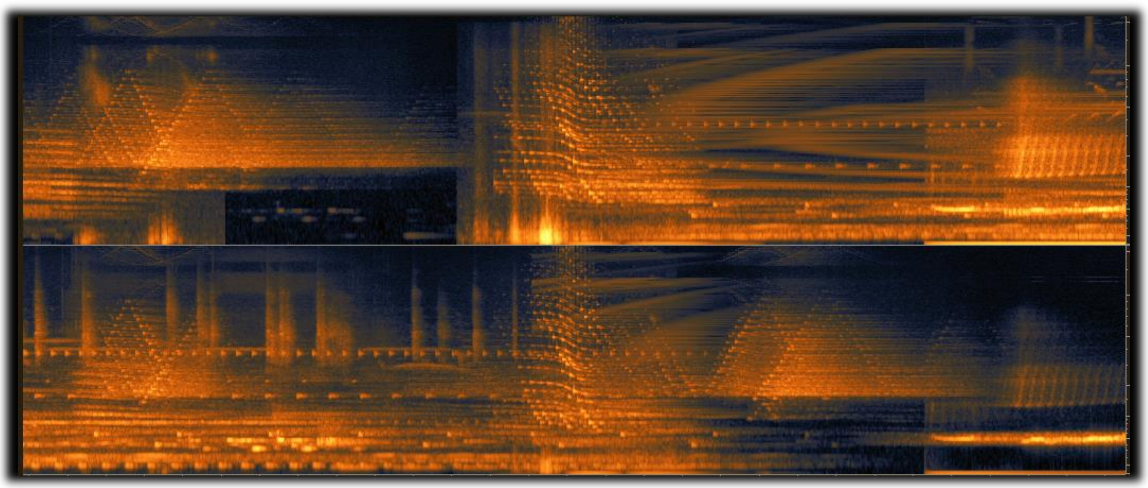

*Figure 10.3 Patterns in excerpt from spectogram of composition 'El Bosque Encantado'. Sound: 'Spectral Canopies' in offline website ; **'Installations and compositions > Surrounded>Spectral canopies'** in the accompanying offline website.*

Further explorations revealed the high pitched twittering of birds made a sound akin to laughter when pitched down. Ornithologist Chris Canaday, author of 'Birds of Ecuador' (Canaday, 1997), noted after listening to some adjusted recordings that some birds' high pitched calls when slowed down were almost identical to the audible cry of completely different species of birds. In the included example, an Ecuadorian bird (*Thamnophilidae*) sounds like the call of various owls, such as the mottled owl, when slowed down (**installations and compositions > Surrounded > Bird Slowed**: This sound features the original speed at the beginning and is gradually pitched down). Perhaps strangest of all was the Morse-code-like calls of crickets and other insects. The pulses of these calls are organized into discrete packets, each of which contained varying numbers of pulses (**fig 10.4**). These sequences of pulses appear so complex and varied that it is hard not to speculate that they form a kind of syntax and communication beyond mere reproductive or territorial signaling.

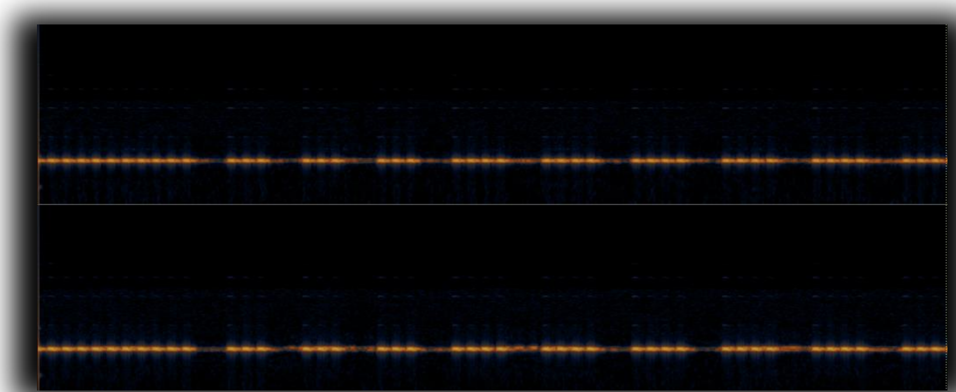

Figure 10.4 Cricket and insect sounds when isolated exhibit Morse-code-like discrete sequences of pulses. The Morse-like sounds were isolated and formed the core of the sound sources in the installation 'The Code' in Brazil. Sounds can be hear din the offline website ***'Installations and compositions > The Code***

Synthesised sound sources were also used in the composition. These were modulated by the electrical signals in the plants in various ways apart from pitch shifting. The parameters of granular synthesis could also be changed by plant signaling. For example grain spacing, grain size and grain shape were all possible to modify in real-time. Other objects such as filters were also employed as well as more conventional effects such as delays and reverbs. Using unconventional sound processing techniques allowed texture as well as pitch to sonify signaling. Video explanations of the max patches used can be seen in the offline website **(offline website > software > surrounded)**

10.5 THE MYCORRHIZAL NETWORK

As previously mentioned, evidence suggests that the forest communicates underground via a system of tree roots interfaced with fungal mycelia known as the mycorrhizal network (Song et al., 2010) (**fig. 10.5**). The exact nature of signaling across the mycorrhizal network is poorly understood. Aside from action potentials in individual plants, some studies show that electrical activity has been found in the mycelium of fungi (Olsson, 1995) and the roots of plants (Baluška, 2004). I wanted to create a system that could detect if such signaling across the mycorrhizal network may be electrical or at least electro-chemical and which was more sophisticated than the previous attempt in 'Invisible Forest'. Current scientific consensus maintains that it is most likely to be chemical signaling though electrical signaling in plants is gaining increasing acceptance and interest. The system described here would work equally as well for chemical signaling as electrical signaling, though electrodes would have to be replaced by the equivalent chemical sensors.

10.6 LOCALISATION OF ELECTRICAL ACTIVITY IN THE NETWORK

Spatial audio is extremely applicable to sonifying biological networks in situ. Networks of communication in the forest are by their very nature spatial or 3D. Trees form *nodes* in these networks (**fig. 10.5**). Therefore it seemed logical to space speakers around the forest at key nodes which, in combination with electrodes, could act as indicators as to where such activity was taking place (**fig. 10.6**).

Broadly speaking, if there is a signal in a particular tree a sound comes from that tree; if a signal appears in one tree and then shortly afterwards at another nearby, then ideally the sound should pan along the route between those two trees. This technique for mapping trajectories with sound as well as other spatial audio techniques used in these installations are explained in a video in the offline website **(software > trajectories and software > trajectory mapping).**

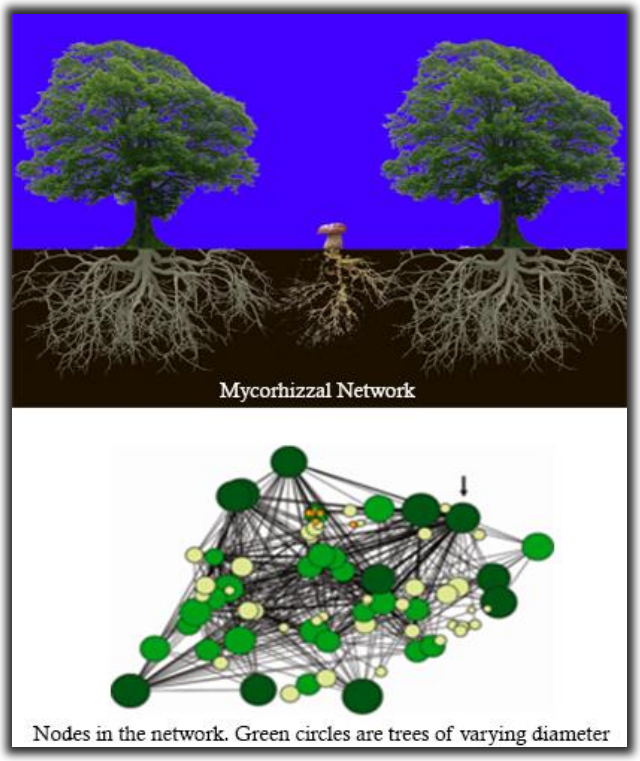

Figure 10.5 The mycorrhizal network (above) is a network of tree roots and fungal mycelium through which trees communicate. Trees act as nodes in the network; larger green circles (below) represent larger trees which generally have more connections.

Though this kind of research is in its early stages, with developing technology, sonifying these networks could become a lot more accurate in the future and we will be able to indicate if, where and when signaling is taking place between trees with more exactitude. For work described here there was a maximum of eight electrodes in the forest which were represented by eight speakers. Interpolation between the nodes can give an idea of how signals may be travelling in the network, though obviously the more points on the network which can be measured, the greater the resolution and more revealing the sonification will become. In this way by panning sounds between trees as they exhibit activity, the audio spatialisation can give some sense of the network at play. As well as panning, volume, pitch and granulation changes throughout the network can also give some indication of the extent of electrical activity and what form it takes. Different types of sound can reveal different aspects of the signals in different ways and allow activity to give rise to different artistic results. Although this work was considerably more advanced than 'Invisible Forest', it still represents a fairly basic prototype for such a technique; however the system is robust and can be easily adapted to incorporate more electrodes should more portable data acquisition devices with more channels become available.

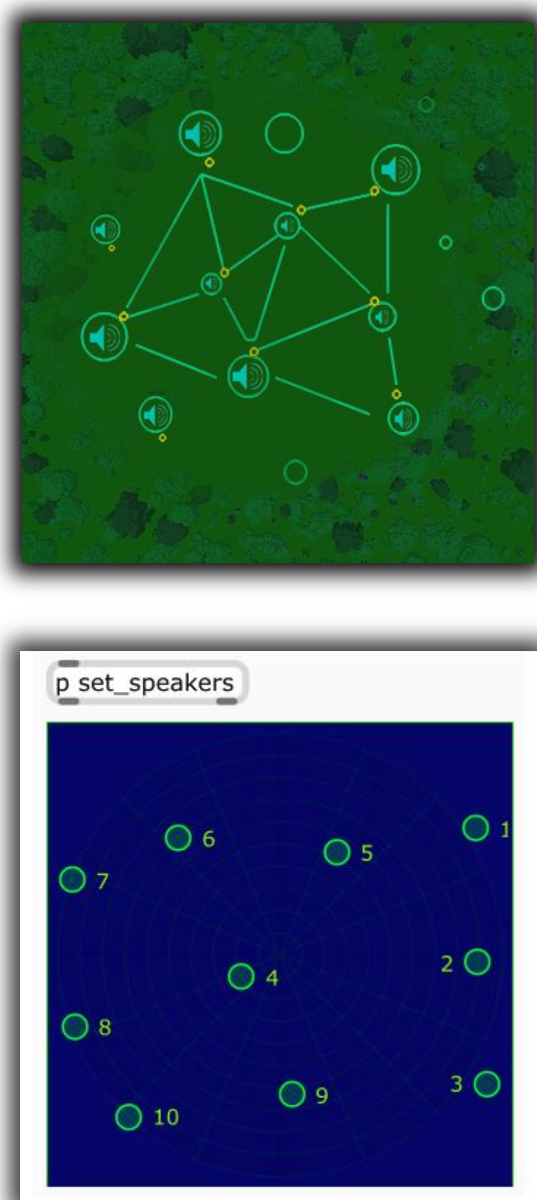

Figure 10.6 (Left) This shows a small patch of forest which in which electrodes have been placed. Yellow dots indicate electrodes. Next to them are small speakers at key nodes of the network. Lines show the directions that signals could take between trees

10.7 SPATIALISATION TECHNIQUES AND IMMERSIVENESS

As mentioned earlier I started working with non- peripheral speaker arrays as my aesthetic objectives could not easily be met by Ambisonics and wavefield synthesis (WFS). Therefore, speakers were used which were in much more irregular arrays designed to map the forest network with disguised speakers close to the listener and indeed which the listener could walk around (*around sound*) (**fig. 10.6).**

The spatialisation here made significant advances on 'Invisible Forest' in several ways. With regard to plant signaling, in 'Invisible Forest' there were just four speakers next to four electrodes in a square. These four speakers emitted a bell or bird sound when the signal passed a certain threshold. Here the speaker arrays were designed more organically so that electrodes and their accompanying speakers were placed next to important 'nodes' in the forest network. Signals in a particular place could affect the whole 'web of sound' in the forest by changing parameters such as gain on other nodes, giving the effect of sounds 'rushing' towards the place where a signal had taken place, creating 'ripple' like delay effects that emanate from where a signal takes place and spread throughout the forest **(offline website: see videos in Software > 'Gain focusing in the Forest Network' and 'Surrounded').** Effects were also placed on the specific channels relating to a particular tree, so as sounds flew around the forest elements of their sound would change according to the signals in that particular node. For example, node 3 might have a pitch shifter on it which was connected to the plant signals. As a sound was panned round the forest, as it passed that particular speaker its pitch might change in accordance to the signal but only in that speaker. Of course many different effects apart from pitch shifting could be used. The development that I found the most effective was randomized trajectories and trajectories that were controlled by signals which shall now be described.

10.8 TRAJECTORIES THROUGH THE FOREST

As well as static sound sources that stayed by particular trees, I wanted to have sounds that would appear to 'float' and wind their way through the trees. The panning used to achieve this bore more in common with DBAP than Ambisonics or WFS. ICST's Max Ambisonics equivalent panners were used with generally low directivity so that their localisation was sharper and the accuracy of localisation was increased. However, directivity can be increased if necessary, to plug holes in the panning between any speakers which were quite far apart. For example, in 'Mycorrhizal Meltdown' trajectories which had to pass between speakers that were far apart had their directivity increased. A map of the speaker array in the forest was entered into ICST and then sounds could be automated on a trajectory around this map or be controlled by bioelectric potentials in the plants (**Fig. 10.6**). This works using adjustable algorithms. For example, if there is a signal in tree one and then shortly after in tree two, the software will instruct the sound to pan between those two trees. The delay time between the two signals can be adjusted to approximate the time it would take a signal to travel between the two trees, and the speed of the panning can likewise be adjusted.

10.9 MULTIPLE MOVING SOUND SOURCES AND AUTOMATION

These installations began using many samples several of which were always playing simultaneously. How sparse or crowded the soundscape became depended on the value of the numbers and dials titled 'lights' 'forest' 'shadows' in the top right hand corner of the patch 'Surrounded'. These could be used live to adjust the overall tonal quality and mood of the piece. As mentioned, each sound had its own trajectory through the forest. This was accomplished using multiple ICST objects in poly objects in Max. Because these trajectories passed along different routes through irregular speaker arrays and because there were hidden speakers close to the listener, it gave the impression of sounds coming very close to the listener. Reverbs, delays and granular artifacts on the sounds were panned slightly behind the principle sound source to give the effect of *sonic trails* being left behind them.

10.10 READING THE SIGNALS

It is extremely difficult to read electrical signals in this network as roots are, obviously, underground and placing electrodes accurately beneath the earth presents abundant technical obstacles especially in tropical rainforests. Invasive electrodes can be introduced to tough or woody roots. Action potentials and variation potentials are found throughout the plant so if inserting electrodes into the roots proves impractical then inserting them into the phloem as well as surface electrodes on leaves presents an alternative. **Examples of the signals being read and modified in real time can be seen in the attached video in the offline website > Installations and Compositions > 'Action Potential'.**

10.11 INTERACTING WITH THE FOREST

Ornithologists and even hunters are known to use a technique known as 'playback' (Sibley, 2011) (Wei, 2010) to call sought after birds or animals so they can be photographed or hunted. This works by reproducing the call of a certain animal or bird so that it will come to find a mate or investigate who is impinging on its territory. Many of the sound sources used in the installations were originally field recordings from the Amazon which were transformed in the various ways already described. It is perhaps not surprising that many creatures seemed to be attracted to the area during composition. There is an ethical consideration here as well; it was desirable that the installations did not interfere too much with the behavior of fauna. For this reason the installations were always done under the strict supervision of park staff and local indigenous groups to ensure minimum impact.

Spectrograms show that sounds in the rainforest have evolved to occupy different frequency bands almost like the different frequencies of broadcast radio waves. There is a surprising degree of separation both in the frequency and time domain, which, it could be speculated, is to avoid interference with each other's 'broadcast range' (**fig. 10.7**) . Indeed, research has shown that birds may vary the pitch of their song in order to avoid them being masked by insect noise (Kirschel, 2009). Although many of the found sounds used in the composition were radically altered, if they still occupied the same frequency band this seemed enough to attract fauna,. Nights in which no composition took place seemed to attract less activity of this kind. Though this is an entirely subjective observation, no objective data could be gathered, and to show the true extent of this would require significant further research. Such research would require a completely different kind of equipment to that which as available to me, such as camera traps and motion sensors. Further studies might indicate how similar to the original animal call playback has to be in order to elicit a response. This could give rise to a better understanding of which characteristics of sound are important in animal communication in the wild, for example frequency, rhythm, timbre or form.

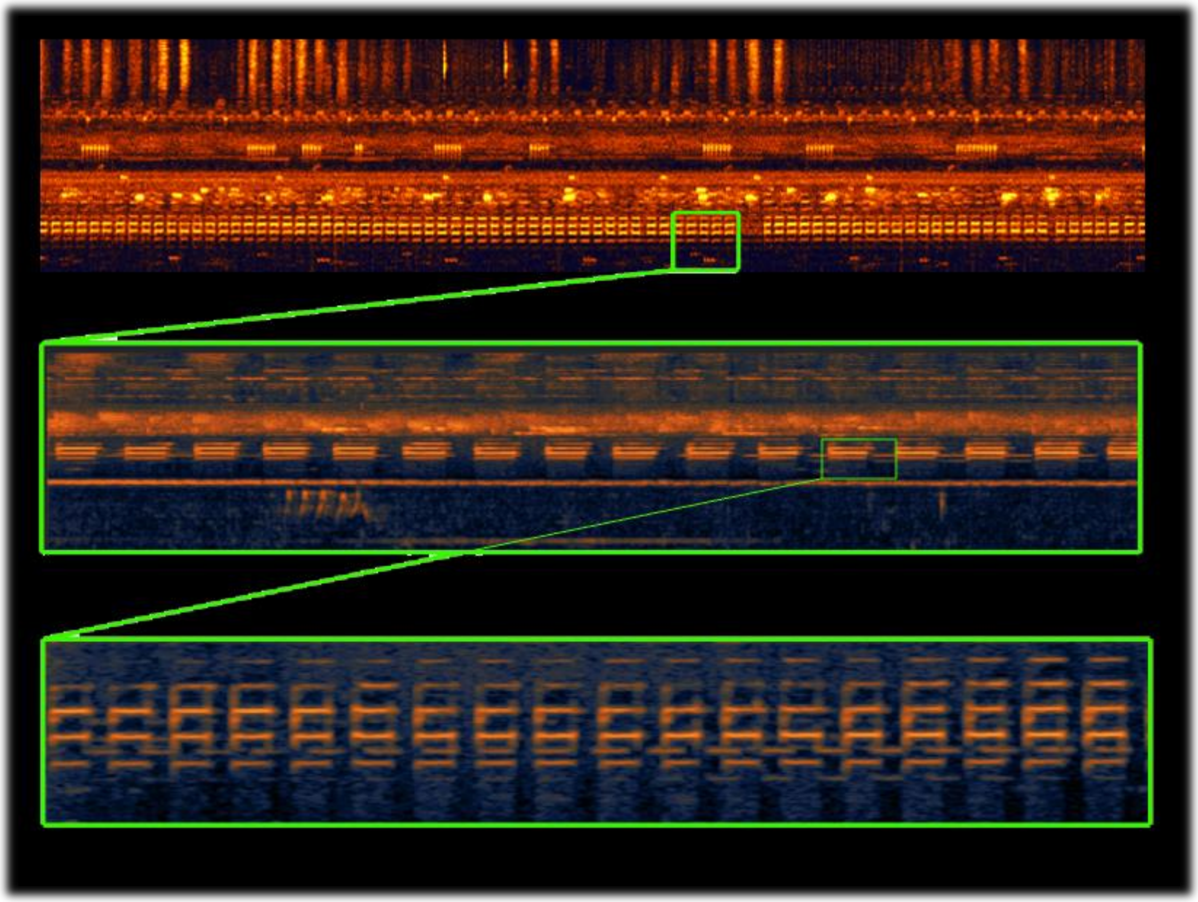

Figure 10.7 The top spectrogram shows a typical rainforest at dawn with different sounds exhibiting a large degree of separation as if occupying the different frequency bands of a radio. Zooming in and isolating different sounds and then processing their pitch and duration provided virtually infinitesimal sound materials to form the basis of composition.

10.12 THE EFFECTS ON FLORA; PLANT RESPONSES TO COMPOSITION

Different sound sources did not appear to immediately affect electrical responses in the plants at any point and laboratory experiments which I performed at LINV appeared to confirm this. That is not to say that sound does not affect plants; in fact several experiments strongly suggest that they do (Lirong, 2010) (Tianzhen, 2009) but a thorough investigation into this phenomena would involve testing thousands of species and is beyond the scope of the current work. However, during many hours of composition in the forest with electrodes attached to plants, no discernable difference in signaling was observed between when the sounds were playing and when they were not.

10.13 How did the three installations differ from each other?

Excerpts can be heard on the offline **website > compositions and installations)** and in the audio folder on the **USB drive> Audio > Surrounded, The Code, Mychorhizal Meltdown > Surrounded quad.wav**

The first installations were 'The Code' and 'Mycorrhizal Meltdown'. These installations converted electrical signals from False Bird of Paradise (*Heliconia psittacorum*). These pieces explored the idea of the forest being a giant signaling network or a kind of fax machine. The inspiration for the pieces was not just the electrical or chemical signals passing between the plants but the audio signals in the forest as well. New research has shown that audio signals from animals are able to interact with plants and may form another form of communication between the plant and animal kingdoms (Schöner, 2016). Just as it is impossible to understand the messages being communicated via a fax machine by listening to it, I imagined in the rainforest that I was surrounded by its giant, natural, far more complex equivalent. I imagined that sound, smell, light and chemicals were being used all around me to communicate information, the meaning of which was unfathomable to most of mankind. I wanted to make the complexity of the audio signaling more apparent to the listener, to bring attention to the organized sonic minutiae that might otherwise have been lost in a wall of sound. Entire soundscapes could be found within the briefest fleck of noise which naturally occurred outside the range of human hearing, and it is these details that I wished to use as the building blocks for the compositions. Aesthetically, 'The Code' was much darker than the next two installations. On reflection I felt the installation was visually less convincing than the other two because it was in a garden in the center of a large modern building, highlighting the importance of visual cues. As was the case with all of the installations, this was to some extent a live performance over three days as well. I was constantly interacting with and responding to the sounds as they were produced by changing parameters as the soundscape evolved. In addition to being modified, some samples were triggered by action potentials. These sounds would emanate from the location of the signals but then proceed to 'spread' outwards, like ripples in a pond. This was achieved using delay lines and automation in conjunction with ICSTs Ambisonics equivalent panners..

The second installation 'El Bosque Encantado' developed the installation in several ways. It converted signals from three different species: *Tradescantia, Anthurium* and *Fuscia Boliviana.* Firstly from a compositional point of view it was decided to balance the soundscape with lighter as well as darker sounds. I did this by organizing sounds in to two groups (light and dark) that were randomly selected and then modified by signals. Although there were no more looping soundscapes, some sounds were still triggered independently before they were modified by the signals. I wanted the soundscape to have a more organic feel. I therefore introduced a randomizing element as to how frequently these samples were chosen. If intervals were too regular it gave the installation a mechanical feel. The installation was in a small 'cloud forest' in the Botanic Garden and the speaker positions and distances replicated the setup that was used during composition in Jatun Sacha. As such the installation was transplanted from one site to the other. As there was a greater variety of plants here it was possible to have a more diverse array of plant *musicians*. An educational element was also introduced to the installation on the request of the Botanic Garden. A stall at the beginning of the installation explained the principal science that had informed the piece before the public entered the space. This is something that I wasn't entirely happy about. I would prefer people to go into such installations without knowing anything about the background, and then, should they be interested they would have the opportunity to learn more about it if they so wished. Framing people's perceptions of a piece of art verbally before they have a chance to experience may deprive people of the chance to form their own impressions first.

'Surrounded' introduced the rainforest field recordings again and combined them with the self-generating sounds. This was the first time I had introduced sounds recorded over several kilometers of rainforest into a much smaller space (20 metres by ten metres). Many people in La Paz (a city high in the Andes) had never heard the sound of the rainforest before and were amazed that such a huge variety of sounds was present in the forests of their own country - the forests in the mountains being largely silent in comparison. I, in turn, was curious as to whether the sounds had any effect on the plant signals. The sounds used were similar to those used in 'Bosque Encantado' but the spatialisation was modified to fit the rather unusual elongated space. Also, plants created 'drone-like' sounds at certain points in the installation.

As mentioned previously the choice of location is also an important creative decision, especially with site-specific work. In the case of 'Surrounded' I chose a small tropical botanic garden in the middle of a park, surrounded by the busy city of La Paz. This tiny magical forest and the traffic noise whirling around it became part of the composition and formed the perfect metaphor for the Amazonian forest being threatened by ever increasing urbanization.

11 INSTALLATIONS: GARDEN OF MEMBRANES 2.0

Figure 11.1 'Garden of Membranes' at the Naughton Gallery, Belfast

The second instance of 'Garden of Membranes' is a permanent work and represented a significant upgrade to the original installation. In many ways it combined the two installations of 'Garden of Membranes 1.0' and 'Surrounded'. A video of the installation can be seen with accompanying audio in the offline website **(installations and compositions > Garden of Membranes 2.0).**

The centerpiece for 'Garden of Membranes 2.0' was 3D printed in Birch ply, and will continue to be used in both artistic events and for scientific purposes. It ran for three weeks at the Naughton Gallery, Belfast, Northern Ireland in 2015. 'Garden of Membranes 2.0' detected electrical signals in *Persea americana, Ficus benjamina, Ulmus parviflolia, Dypsis lutescens* and commercially available mycorrhizal fungi. The deliberate inclusion of mycorrhizal fungi is significant and as the installation matures over the months and years, it is hoped that interface between roots and mycorrhiza will increase in strength.

The sounds are part composition and part sonic map recorded in the Amazon rainforest using the technique described earlier but in a slightly different way. In 'Bosque Encantado' the transferred map is the same size as the original recording. Here, the sounds were recorded as before with many microphones placed in different parts of the rainforest and then recreated with speakers in the same relative positions **(fig. 11.4).** However in this case an area of rainforest 10,000m² was reduced to a Bonsai forest 1m², as well as the larger speakers around the gallery.

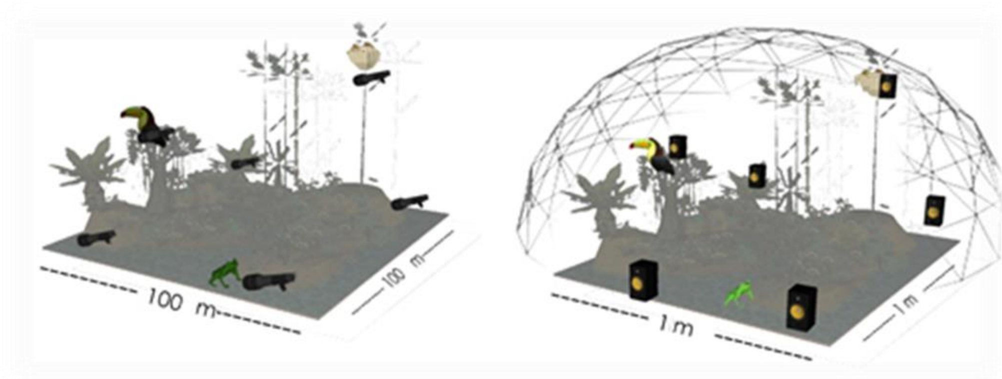

Figure 11.2 Firstly a 'sound map' is created of the rainforest using various microphones (left). Secondly this sound map is reproduced in miniature by placing speakers in the same places the microphones were in a tiny Bonsai forest (right.), this is a far smaller scale than was attempted before, here it is scaled down to around 1m² whereas in 'Surrounded' it was around 500m².

The 'Garden of Membranes' exhibition at the Naughton Gallery was in a much larger space and featured many more speakers around the room. The 3D printed centerpiece allowed for greater integration of the audio technology and miniature ecosystem (**fig 11.1**).

11.1 DATA LOGGING AND TIME LAPSE REPRODUCTION

For 'Garden of Membranes 2.0' a data logging system was created in Max MSP which allowed the recording of many hours of electrical signals in a multi-electrode array. This data can be played back at faster rates and allow 'time lapse' reproduction of electrical activity in the miniature ecosystem. This allows us to see how signals may be changing over a 24 hour period in much the same way that time lapse photography allows the viewer to see the movements of plants that would otherwise go unnoticed. This kind of data manipulation also allows for new ways to create multichannel compositions and is an interesting creative tool that also provides scientific insight. S**ee Software > Video 5 'data logging' in the offline website for more details.**

11.2 ALTERED SPACES; LIVE RESPONSIVE 3D REVERBERATION

A new element to 'Garden of Membranes 2.0' aimed to alter the way the listeners perceived the space in which they were in. Studies have shown that humans rapidly assess the size of the space they are in by calculating distances using early reflections and reverberation times on sounds generated by the movement and sounds the person makes (such as footsteps) to calculate distances, somewhat similar to a bat's sonar (Zahorik, 2002). This installation sought to subvert this natural process and give the impression that the listeners were in a much larger space than they actually were. The installation was in darkness so that visual cues could not override the audio cues. Microphones were hidden around the installation that would record noises made by the listeners such as speech and footsteps and then reflect the reverberation times back through the 3D speaker system. This fake reverb was designed to give the impression of being in a huge space as opposed to the rather small gallery space. The technique was moderately successful but needs considerable further experimentation to be truly effective. Feedback can be an issue and correct microphone placements would require considerable research and development through trial and error to perfect.

11.3 OTHER ELEMENTS USED IN THE COMPOSITION

11.3.1 **Phloem; Frequency splitter**

Normally when measuring action potentials frequencies above 45 HZ or so are low pass filtered in order to reduce noise (e.g. mains noise). However, there is a possibility that higher frequencies may also contribute interesting information about plant electrical signaling. This frequency splitter divides the electrical signal into many component frequency bands and uses it to alter a component of sound such as a sine wave. When spatialised over several speakers this allows the listener to sit in the middle of the sonified action potentials component frequencies. A video explaining how this works can be seen in the offline website **Software > Multi Frequency signal analysis**.

An example of the sound this software can produce is given in the USB stick **Audio > Garden of Membranes 2.0 > signal splitter.wav**

An idea of how it is used in 'Garden of Membranes' when mixed with granular software can be found in **Audio\5. Garden of Membranes 2.0 > Layered signals.wav**

As well as creative applications this tool provides a useful way of monitoring multiple frequency ranges at the same time.

12 USB DRIVE: SOFTWARE, AUDIO AND WEBSITE

This document is accompanied by a USB drive which contains all the relevant documentation and audio. The website can be opened by entering the folder and double clicking the file named “index.html”.

12.1 SOFTWARE

The software used in the compositions was created in MaxMSP, field recordings were played back in Nuendo. Most of it is designed to work with a Labjack U3 LV data acquisition device and will not function without this device being connected, though it could be adapted to work with other devices. The software continuously evolved in response to creative and scientific problems; in many ways it is an extension of the artwork itself and forms a bridge between scientific and artistic practice. Ideas and software developed here may also pave the way for future research and development. Videos which go into detail about how the software works can be found under the heading **‘software’** in the accompanying offline website.

These include:

12.1.1 Signal Conditioning

This video explains how signals are filtered to reduce noise.

12.1.2 Granular translation

This video explains how signals are translated through granular synthesis.

12.1.3 Gain focusing

This video explains how signals are focused in one area using gain change.

12.1.4 Multi Frequency

This video explains how signals are represented sonically at different frequencies.

12.1.5 Time lapse data logging

This video shows how time lapse data logging works and different ways it can be converted into sound. Some examples of this have been mixed with the above 'multi frequency splitter'; **Audio\5. Garden of Membranes 2.0 > Layered signals.wav**

12.1.6 'Surrounded'

This video shows how the main patch used in 'Surrounded' and other installations works.

12.1.7 Trajectory Mapping

This video shows how trajectories of electrical signals are mapped to trajectories of sound.

12.2 AUDIO

Excerpts of the installations can be heard in the folder marked '**Audio**'. These installations were designed for specific environments, typically using a large number of speakers in an irregular array, using unusual spatialisation techniques and running for several days. As such these audio excerpts can only give a limited snapshot of the actual event. Some larger multichannel files are included with speaker maps, but quadraphonic files are also included for easier playback. Although the spatialisation used was generally far more complex than quadraphonic, this will at least give some sense of immersion though still nowhere near the full range of holophony used in the installations. It is not advised to listen to these files in stereo, however if this is really the only option then 'Quick Time Player' is recommended as it will play back most multichannel files in stereo automatically, down mixing them.

12.2.1 **'Invisible Forest'**

For this file, I tried to evoke some sense of the original spatialisation by placing the listener in the centre of the four trees from which the bells sounded.

12.2.2 **'Garden of Membranes 1.0'**

This was extremely hard to represent at a quadraphonic or stereo level. Capturing the interplay between the miniature speakers and the larger speakers is especially difficult. In order to evoke some sense of the original spatialisation I placed all the sounds that were originally in tiny speakers in the Bonsai forest on the right speaker alone, with reduced volume, with sounds emanating from there and filling the larger stereo field with more volume.

12.2.3 **'Surrounded', 'The Code', 'Mycorrhizal Meltdown'**

This folder contains a mix down of a 48 channel piece into quadraphonic and is called **surrounded quad.wav**. It contains all three installations, and joins them together using the field recordings that were ultimately used in 'Surrounded' and 'Garden of Membranes 2.0'. It also contains a file '**The Code live in the Forest in Omaere.wav'** which is a live recording of the 'The Code' being composed in the forest. The sounds of the composition can be heard blending with the natural sounds of the forest and gives some insight into the choice of sounds used in the installation. ‘Spectral Canopies’ is a stereo file derived from the installation ‘Bosque Encantado’.

The other folders contain various versions of the different installations in stereo, quadraphonic and larger multichannel file formats.

13 CONCLUSION AND FUTURE DIRECTIONS

In this thesis I have described new developments in the field of plant electrophysiology and sonic art, including a new approach to monitoring electrical activity in the field, new spatial audio techniques that can be used for artistic and scientific ends and new ways of turning signals into sound. The argument has been made that rather than art conforming to a 'service-subordinate' model of interdisciplinary research, combined research involving and science and art can be conducted in a way that allows both fields to progress.

My original research question was 'How can plant electrophysiology and art be integrated?' This question and the sub research questions have been answered by specific examples throughout the text which show how both fields have inspired advancement in the other. However, the overarching answer, which I believe applies to any interdisciplinary research, is that true integration of such disparate disciplines can only come about if both are respected and not compromised by the other. The conclusion I have drawn is that both disciplines must stand independently and separately from each other as if they were two pillars - they must be self-contained enough to stand alone if the other was not present, but it is the space in between those two pillars where a true synergy can occur.

Historically science and art were not considered to be such different fields, and I found the curious and open minded attitude of scientists in academia to be a real inspiration throughout the thesis. I have therefore also reached the conclusion that science and art are in fact infinitely compatible and in many ways the processes that cause scientific discoveries are similar to the ones that cause artistic ones. It is not inevitable that such combinations will produce badly conducted science and unimaginative art, they can feed into each other in many innovative ways, but the artist must be able to follow their muse, just as the science must be diligently and rationally conducted.

Other ‘sub’ research questions also provided the basis on which a contribution to knowledge was based. These were ‘How can the artistic side of science-art research be more than just the sonification of data?’ This question was answered by showing many novel ways of converting signals into sound such as granular synthesis, by using spatial audio and by making the argument that the aesthetic considerations of such conversion are as important as the scientific ones.

‘How can art contribute to scientific understanding?’ It was demonstrated that spatial audio holds a unique potential to sonify electrical signals in ecosystems and networks such as a forest by creating sounds in the exact places that electrical activity was taking place. Although the software and mapping techniques employed in the research are in their initial phase of development, they have never been attempted before and form a basis for a research model and artistic approach for creating more developed work in the future.

How can this research inspire novel artistic work in the field of spatial audio? Several new spatial audio techniques have been demonstrated. The need for an authentic natural soundscape of the rainforest inspired a new form of 3D audio recording and reproduction. The need to track signals as they moved inspired site specific spatial audio installations that included sounds moving along trajectories that could come ‘close to the listener’ which combined with cognitive cues did so in a more effective way than that offered by conventional techniques. The need to have a more controlled environment to test signals inspired the use of a ‘miniature’ multichannel sound sculpture using spatial audio techniques that had not been attempted before (microspatialisation). The fact that research took place in the natural world itself, rather than the lab, engendered site specific sound art which relied to a large degree on spatial audio, but also on the use of sounds that fitted the location. The case was also made for increased use of subtle cognitive cues which can help audio ones be more effective, and for the choice of location to be considered as an important part of the composition as well.

Whilst none of the sensors used in the research were in themselves groundbreaking, their mode of application itself was novel, and as one of the main impediments to the advancement of the field is the lack of clear, concise technical knowledge that is readily available to artists, a robust technical approach also helps advance the artistic side of the field as well. By consulting with numerous plant electrophysiologists about techniques specifically relevant to art/science projects, and clearly explaining these materials and methods in one easily accessible document, it is hoped that it will prove useful to other artists working in the field of plant electrophysiology and art.

13.1 PERSONAL REFLECTION ON THE ARTISTIC PROGRESS AND DISCOVERIES THROUGHOUT THE RESEARCH

When I started the project I was using often looped field recordings which acted as a static backdrop (almost like a painting) in which certain elements could be triggered by the electrical signals when they passed a certain threshold, such as the 'bell sounds' in 'Invisible Forest'. Apart from the timing and the pitch of these bell sounds the piece was fairly predictable to me, just as a prerecorded piece of music with a few algorithmic components may be. It should be noted, however, that even at this early stage of the research the installations were very much a live performance which consisted of me adjusting levels, textures and element of the soundscape in real time to suit the moment. However, later installations consisted of more sophisticated software that I created myself. The max patch that I created for 'The Code' did not repeat itself on a loop. It constantly changed and manipulated sounds in a variety of unpredictable ways. I had to train this software by listening to it for hours on end and refining it to a sonic state that I found acceptable. Over the course of the next few installations this software was continuously adjusted and tweaked evolving into a finely balanced system in its own right. It had many facilities and could also be used as a live production tool. Creatively this proved to be a major breakthrough for me as artist, custom making my own tools to fulfill certain artistic needs broadened my palette considerably and I have used the software for several installations recently to great effect, installations that had nothing to do with science or plants. Throughout the research I also became increasingly aware of the importance of cognitive effects, context and subtlety in installation art. Experimenting with different types of spatialisation was an activity I found extrememly rewarding. Mapping thousands of square metres of rainforest and then miniaturising this map and reproducing it in a tiny Bonsai forest was something that fulfilled my penchant for the surreal as well as being a technical curiosity with potentially more prosaic applications in the future.

Sounds travelling along unpredictable spatial trajectories in the forest, and morphing into different shapes as they travelled, fulfilled the original visions of a forest full of subtly shifting chimeric forms that I had envisaged at the start of my research.

13.2 FUTURE DIRECTIONS

There still remain many gaps and unexplored areas both technically and artistically in this field. I have no definitive answers on whether or not plant root networks form a neural net and it is still unknown whether or not plants signal to each other using electrical signals or if electrical signaling is only present within individual plants. However, I know what path it would be necessary to walk in order to answer those questions conclusively, and I have created systems and approaches that can be developed more in the future to discover the answers to this question, and perhaps stimulate further research in this area.

One of the main goals of any future developments would be to develop higher resolution sensor systems ideally which do not rely on electrodes. Mycologist Jim Bell suggested in a personal communication that graphene plates might be used and the mycelium encouraged to grow between them. When discussing the mechanisms by which information and instructions are distributed amongst the roots of individual plants, Stefano Mancuso in his book 'Brilliant Green' states there may exist some form of electromagnetic field allowing for communication between the tips of the root radicles (Mancuso, 2015). If this is the case then perhaps some kind of electromagnetic sensors could be devised which could give similar results as the new imaging techniques used in brain scanning (Homma, 2009).

It has become obvious to me throughout the course of the research that electrical signals form only one facet of plant signaling and behaviour. Chemical signaling and airborne signaling may be just as important as electrical signaling with regard to plant communication and may work in tandem with it. This again is still an area that is far from clearly understood. Making Jasmonite or other airborne signals visible using dyes, gases and other types of sensors could present another interesting visual aspect to the installations as well as revealing more about how ecosystems communicate. One very obvious next step is to incorporate light into the installations. These lights, changing in accordance with the signals, would create further avenues of artistic exploration and, considering our visually fixated culture, probably have more impact on the minds of the viewers. I have several ideas on how this could be achieved. One idea I would like to develop would be to dot the forest floor with thousands of LEDs connected to transistors that act as threshold devices, and when the signal passes a certain threshold the LED lights up. This would allow us to see how these signals travel, if at all, in their natural environment. A cursory investigation showed such a device could be produced very cheaply.

I intend to work on a javascript object for Max MSP which will allow the panning of sounds along trajectories of signals to be done in a more flexible way. For example, if you have thirty or a thousand electrodes the java object could be adjusted merely by typing the number of electrodes into it.

13.3 CONCLUSION OF THE CONCLUSION

Real, complex electrical signaling in plants exists but is yet to be fully harnessed by the wider artistic community as an avenue for creative expression and genuine interaction with the plant kingdom. The relatively few scientists in the field who are fully qualified to advise them are often too busy to offer advice and sometimes do not even agree, and some of the technical assistance offered to artists it not always by people familiar with the field.
However, despite these issues relatively few technical adjustments need to be made to allow correct implementation of plant electrophysiological techniques in artistic practice. With increased cooperation between scientists and artists such collaborations could provide a mutually beneficial synergy that sheds light on undiscovered areas of the science, as well as making research more accessible to the public. Also, by adopting a more egalitarian approach to interdisciplinarity, they can allow for the creation of innovative and inspiring new creative work and a true integration of science and art.

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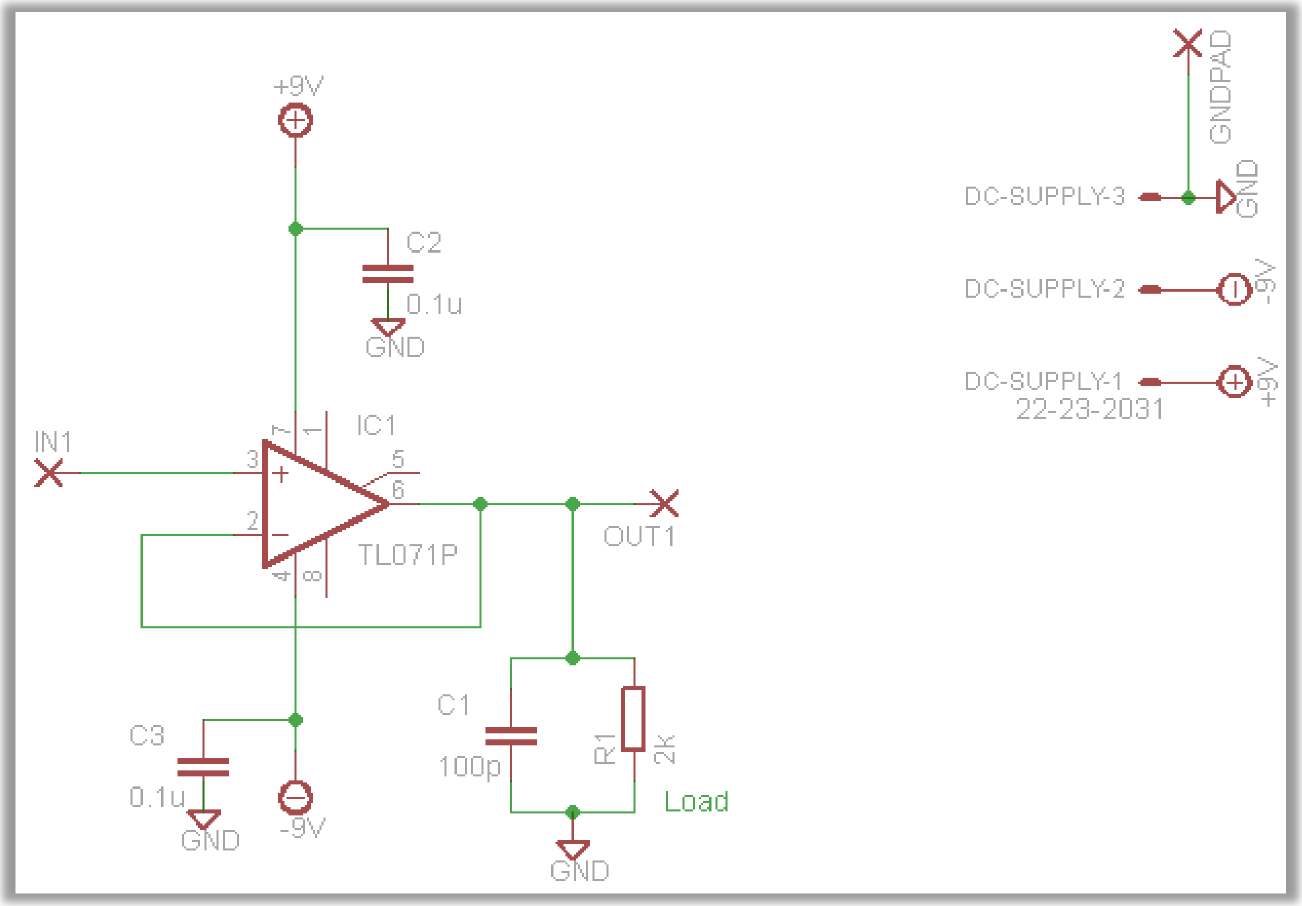
Appendix A

The Garden of Earthly Delights, Hieronymus Bosch 1490 - 1510

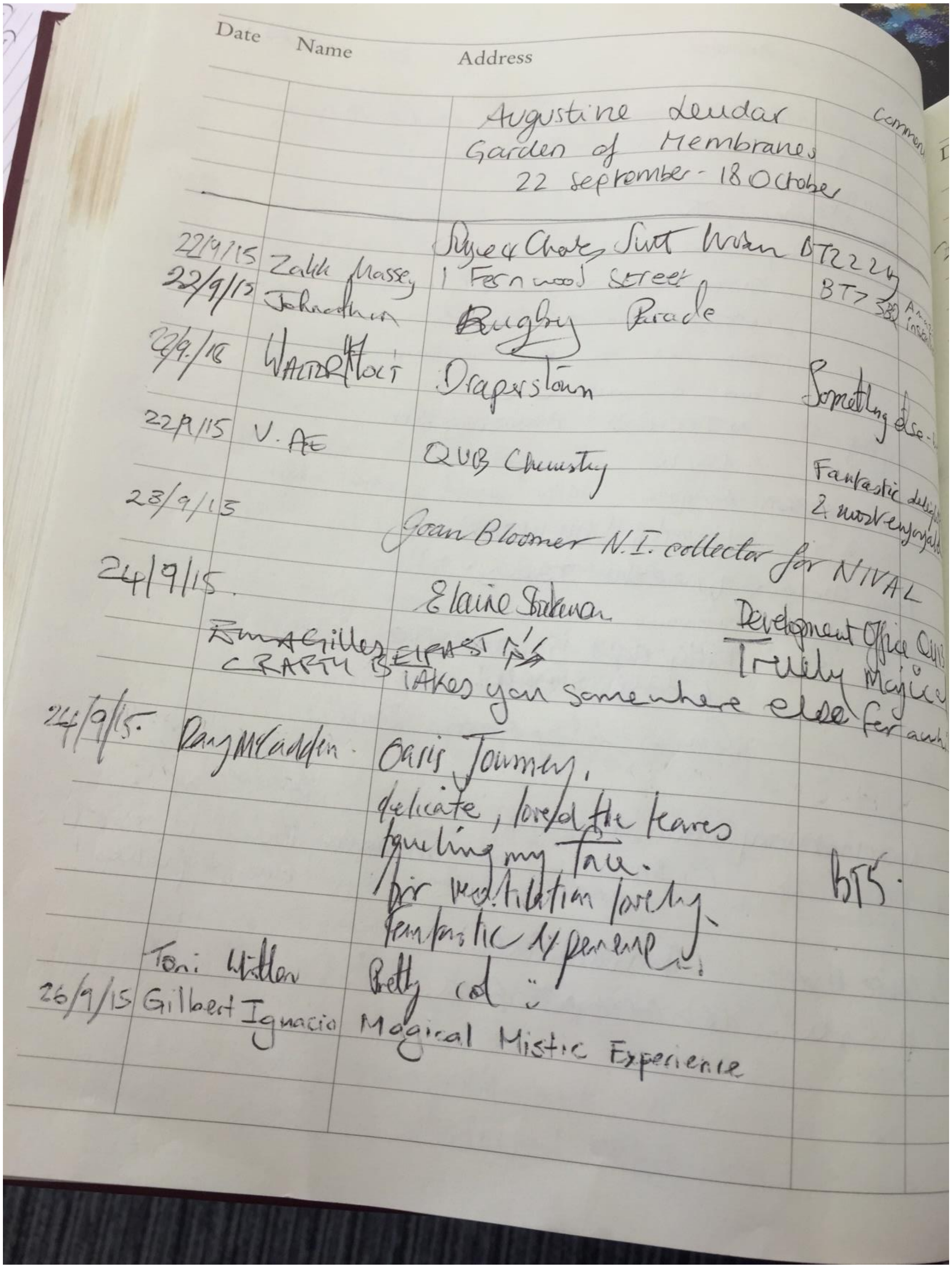
Appendix B

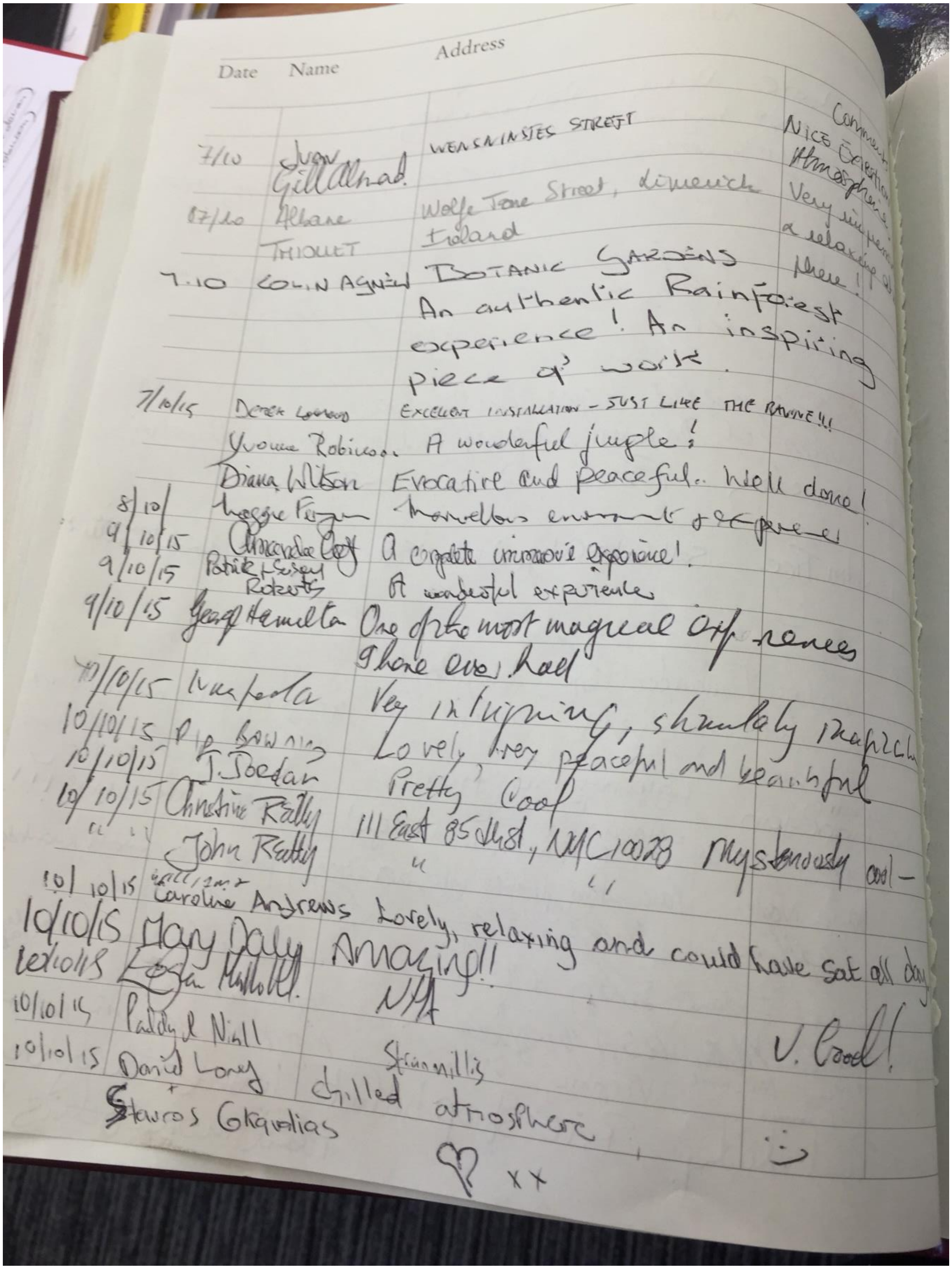
PCB and Schematic



Appendix C

Feedback from Garden of Membranes 2.0 – visitors book at the Naughton


Date Name Address
Augustine Leudar
Garden of Membranes
22 September - 18 October
22/9/15 Zakk Massey 1 Fernwood Street BT7 3
22/9/15 Johnathan Rugby Parade
22/9/15 Walter Holt Draperstown Something else
22/9/15 V. AE QUB Chemistry Fantastic
23/9/15 Joan Bloomer N.I. collector for NIVAL
24/9/15. Elaine Stakeman Development Office QUB
Truly Magical
Takes you somewhere else for a while
24/9/15. Oasis Journey,
delicate, loved the leaves
touching my face.
BT5.
Fantastic experience
Toni Whitten Pretty cool
26/9/15 Gilbert Ignacio Magical Mistic Experience


Date
Name
Address
Comments
Nice Exhibition Atmosphere
Very impressive a relaxing place!
07/10 Albane THIOLLET Wolfe Tone Street, Limerick Ireland
7.10 COLIN AGNEW BOTANIC GARDENS
An authentic Rainforest experience! An inspiring piece of work.
7/10/15 EXCELLENT INSTALLATION – JUST LIKE THE RAVINE!!!
Yvonne Robinson. A wonderful jungle!
Diana Wilson Evocative and peaceful. Well done!
8/10
9/10/15 A complete immersive experience!
9/10/15 Patrick + Susan Roberts A wonderful experience
9/10/15 One of the most magical experiences I have ever had
10/10/15
10/10/15 Lovely, very peaceful and beautiful
10/10/15 J. Jordan Pretty Cool
10/10/15 Christine Reilly 111 East 85th St, NYC 10028 mysteriously cool –
John Reilly
10/10/15 Caroline Andrews Lovely, relaxing and could have sat all day
10/10/15 Mary Daly Amazing!!
10/10/15
10/10/15 Paddy Niall
10/10/15 David Long Stranmillis Chilled atmosphere
V. Cool!
xx

Appendix D

Garden of Membranes 1.0 in Bolivia's Deber

BRÚJULA SÁBADO 7 DE JUNIO DE 2014 EL DEBER WWW.ELDEBER.COM.BO

Misceláneas

AUGUSTINE LEUDAR. Con más de 20 años investigando las plantas y las formas que tienen de comunicarse, el científico, artista y músico experimental llegó a Santa Cruz para hablar de su experiencia en estos campos

ENRIQUE CANEDO

SONIDOS VIVOS. Augustine busca recrear la naturaleza en su música. Participó del afamado festival Glastonbury.

LEUDAR: EL LENGUAJE DE LA NATURALEZA

ADHEMAR MANJÓN
EL DEBER

El sonido de la naturaleza es la marca registrada de Augustine Leudar, un tipo de unos 40 o 41, quizás 42 años (dice que no recuerda su edad exacta) que lleva como 20 estudiando las plantas y los sonidos que emiten.

Las plantas se comunican entre sí, no con un lenguaje articulado, por supuesto, sino a través de signos eléctricos, explica Leudar, que llegó a Santa Cruz para participar de la feria cultural La Clandestina con charlas y talleres; estos signos eléctricos en fisiología se los denomina "potencial de acción" y son similares a los que producen el sistema nervioso humano y el animal.

El interés de Augustine en esta área surgió cuando viajó a una comunidad indígena en Perú

Leudar, nacido en el Reino Unido, recientemente estuvo trabajando en Brasil, en plena selva amazónica, como parte de sus estudios de doctorado en el Centro de Investigación de Arte Sonoro, de la Universidad de Queen, en Belfast (Irlanda).

El idioma de las plantas

El interés de Augustine en esta área surgió cuando viajó a una comunidad indígena en Perú; allí, los originarios cantaban ícaros (himnos chamánicos) para relacionarse y entender las propiedades medicinales de las plantas.

Leudar, que estuvo en idas y venidas al Perú por siete años llegó a la conclusión de que estos organismos respondían a los cantos de los indígenas y es lo quiere demostrar con una base científica que va por buen camino, menciona.

En sus estudios, Leudar coloca electrodos en las plantas de una manera que no afecten los signos eléctricos. Mide si hay reacciones o estímulos y si los hay la computadora los convierte en sonido. Es un procedimiento similar al que hizo el estadounidense Alvin Lucier en 1965, cuando presentó su *Music for solo performer;* ahí, Lucier se conectaba electrodos de electroencefalografía en su cabeza y amplificaba las ondas cerebrales. "Antes había una controversia muy grande en torno a esto", cuena Leudar. "En parte debido a unos estudios muy malos realizados en los 60, 70, que fueron desvirtuados rápidamente. Hoy hay un poco más de aceptación", agrega, y comenta de una tésis de la científica Mónica Gagliano aparecida este año que propone que las plantas tienen la capacidad de 'aprender', es decir, tienen memoria.

Música en la selva

Augustine Leudar también hace música, pero no es la convencional que suena en todas las radios o en las fiestas. "A mí lo que me encanta es el audio espacial", dice entusiasmado Leudar. El audio espacial sucede cuando se utilizan dos parlantes para crear la impresión de que la fuente de los sonidos proviene de cualquier lugar, no solo de donde están situados los parlantes.

"Son sonidos envolventes y yo intento crear cosas que son imposibles regularmente", continúa Leudar, cuya especialidad son las instalaciones en las que reproduce las sonoridades de los bosques.

Él fue el autor de la instalación sonora *Biomes at night* que abarcó todo el Proyecto Edén, de Cornwell (Inglaterra), el jardín botánico más grande del mundo.

"Normalmente cuando ponen sonido en un lugar así, sale de dos parlantes, pero no suena igual que en la selva; como yo viví ahí, sí sabía cómo sonaba, tiene sonidos por todos lados. Entonces, rodeamos el lugar con amplificadores y pusimos un parlante gigante arriba que emitía truenos y sonidos imaginarios; la gente caminaba por la noche y escuchaba eso, que sonaba como en la selva. No exactamente igual, pero imitaba a millones de insectos, para muchos era como real", indica Leudar.

El futuro

Leudar se considera más un artista que un académico, sin embargo sus investigaciones con el reino vegetal continuarán. En la feria La Clandestina habló de su trabajo como músico experimental, de la electrofisiología de las plantas y tuvo una pequeña instalación titulada *Jardín de membranas.*

Su trabajo musical puede escucharse completanmente en su cuenta de souncloud. Produce piezas que están dentro del género de música concreta, hipnagógica y también ambiental.

Siente que recién está empezando a ver los frutos de su esfuerzo, sobre todo en lo económico. "Llevo 20 años en esta vaina y recién hace cuatro que estoy haciendo plata", comenta, siempre de manera amable.

Leudar estuvo con otra instalación el año pasado en la sección Shangri La del prestigioso festival de Glastonbury.

Espera venir otra vez a Santa Cruz, donde ya estuvo hace cuatro años y agregar algo de Bolivia a su repertorio ••

Translation :

The sound of nature is the trademark of Leudar Augustine, a man of about 40 or 41, maybe 42 years (he says can not remember his exact age) and he has been studying plants and sounds they emit for 20 years.

Plants may communicate with each other, not with articulated language, of course, but through electrical signals explains Leudar, who came to Santa Cruz to attend the cultural fair La Clandestina of art, creativity, talks and workshops; these electrical signals in physiology are called “action potentials” and are similar to those that produce the human nervous system and that of animals.

Leudar, born in the UK, was recently working in Brazil, in the Amazon rainforest as part of his doctoral studies at the Sonic arts Research centre at Queen’s University in Belfast.

The language of plants

Augustine’s interest in this area came when he traveled to an indigenous community in Peru; there, they sing ícaros (shamanic hymns) to relate to and understand the medicinal properties of plants.

As a result of these comings and goings to Peru for seven years Leudar concluded that maybe plants responded to the Icaros and he was interested to see if there was a scientific basis for this.

In his studies, Leudar places electrodes on the plants in a way that does not affect their natural electrical signals. He then measures for reactions to stimuli and if there are any signals the computer makes them audible. It is a method similar to that made the American Alvin Lucier in 1965, when he presented his Music for solo performer; Hence, Lucier connected electroencephalography electrodes to his head and amplified his brain waves. “Before there was a big controversy about this,” says Leudar. “In part due to very poorly controlled studies in the 60s, and 70s, which were quickly discredited. Today there is more acceptance in the scientific community, “he adds, and says scientist Monica Gagliano appeared this year to propose that plants have the ability to ‘learn’, ie they can remember.

Music in the rainforest

Augustine Leudar also makes music, but not the conventional type ringing out at radios and parties. “what I love is spatial audio,” enthuses Leudar. Spatial audio happens when speakers are used to create the impression that the source of the sounds comes from all around the listener, not just where the speakers are located.

"The sounds immerse you, I try to create things that would be impossible normally," continues Leudar, who specializes in producing forest soundscapes.

He was the author of the sound installation "Biomes at night"which covered the Eden Project in Cornwall (UK), the world's largest botanical garden.

"Normally when people play sounds it comes out of two speakers, but it doesnt sound the same as the rainforest; because I had lived there, I knew how it really sounded, sounds come from everywhere. We filled the place with amps and put up a giant speaker that emitted thunder sounds from above and speakers emitted imaginary sounds as well; people walked through this environment at night , and it sounded like in the rainforest. Not exactly the same as the sound emitted by million of insects, but for many it was real enough"indicates Leudar.

The future

Leudar's research into the plant kingdom continues. At the La Clandestina festival he spoke about his work as an experimental musician, the electrophysiology of plants and had a miniature sound installation called "The Garden of membranes".

His musical work can be heard on his souncloud account. He produces pieces within the genre of music concrete, hypnagogic and ambient music. He feels he is just beginning to see the fruits of labour, especially economically. "I've been doing this stuff for 20 years but it's only the last four years that I've been paid for it" he comments, as always politely. Leudar produced another sound installation last year in the Shangri La area of the prestigious Glastonbury festival. He hopes to return to Santa Cruz, which he visited four years ago and add more to his repertoire.