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The Photosynthesiser

A methodology for mapping environmental conditions, pivotal to the speed of photosynthesis in plants, through sonification.

by

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Author's Declaration

At no time during the registration for the degree of Research Master has the author been registered for any other University award without prior agreement of the Doctoral College Quality Sub-Committee.

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Abstract

Traditionally, the close inspection of data requires visual guidance in the form of displays depicting numeric or graphical representations over time. Sonification offers a way to convey this data through auditory means, relinquishing the need for constant display monitoring. To enable horticulturists to continue to move and work around their environment a proposed sonification mapping system for the key environmental conditions, vital for optimum levels of photosynthesis, has been developed. The outcome of this research was to provide a monitoring system that was both musical and meaningful with regards to data fluctuations and most importantly, could be interpreted by a wide demographic of listeners. A literature review provides an underpinning to both the scientific and artistic merits of sonification whilst a practice-based model was used to develop appropriate musical timbres, offering a natural instrumentation through physical modelling synthesis. Key questions around which musical factors can be used to trigger specific emotions and which of these emotions do we associate with an environment that offers a higher rate or low rate of photosynthesis for plants are explored. Through literary research as well as the deployment and analysis of surveys, a list of musical parameters was identified and a mapping framework designed. To analyse the success of the design, an audio installation was constructed within grounds at the Eden Project. The environmental data of both biomes, tropical and Mediterranean, were sonified into two musical streams and visitors surveyed through quantitative and qualitative methods in an experiment to see if they could correctly associate the music to the biome. The results provided 90% accuracy in the correct identification. It is theorised through this research that the mapping framework designed can be used in the sonification of climate conditions and communicate key traits within each environment.

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List of Key Terms and Abbreviations: Sonification, Photosynthesis, Max, Stochastic, Generative.

CAAC………….. Computer-Aided Algorithmic Composition
CDR……………. Continuous Data Representations
DDR……………. Discrete Data Representations
FM……………… Frequency Modulation
IDR……………. Interactive Data Representations
MBS…………… Model-based Sonification
PAR……………. Photosynthetically Active Radiation
PMSon………. Parameter Mapping Sonification
STEM………… Science, Technology, Engineering, Math
STEAM……….. Science, Technology, Engineering, Art, Math

Fields of study: Computer music composition, music technology, sonification, sound design, human perception.

Introduction

This paper aims to explore a methodology for mapping environmental conditions as sound through sonification. The mapping framework outlined is based upon researching musical factors that are associated with emotional responses of listeners but, additionally, the results of more specific enquiries into human perceptions of such musical factors in relation to the rate of photosynthesis. Throughout the work key questions are raised, explored and answered to help define the framework parameters, to weigh the value of just such a project and the broader future possibilities of this research. Motivation for the research arises from the weaving of art and science in a coalescence that provokes thought and discussion through the integration of these two disciplines. We are living within a segment of the earth's history where our interactions with our environment and its continual downward flux is being seen as a threat to human progression and longevity. Finding new approaches to engaging individuals with consequences of their actions and, in turn, initiating changes to human behaviour potentially could be an outcome of this project, if expanded through future developments of this first manifestation. Initially, it is hoped that the project will seed discussions and activate interest in the wide variability of environmental conditions and of how delicate, interactive ecosystems must be preserved if we are to stabilise the escalating phenomenon of climate change. One of the key requirements of the sonification is that the auditory display created can offer insight into the type of environmental conditions that have acted as the stimulus for the composition, thus creating a relationship between the two mediums. The final installation will be assessed on the associations made by each listener, between the compositions and the environment, as to whether any relationship has been established. In order to judge if such a correlation exists and meaningful associations have been made based on the sonification of data, this paper will provide evidence with which to assess whether the mapping framework design is sound. In working towards this definitive outcome, quantitative research techniques have utilised a series of surveys to quantify opinions on the connection between musical factors, such as amplitude, pitch and tempo, and the rate of photosynthesis in plants.

The collection of data to assess the success of this research was managed through an installation of the sonification at the Eden Project where an electronic voting system was established to collect and store public judgement. The site was chosen as it provided the perfect platform for the recording of environmental data, offering contrasting ecosystems in the housing of two manufactured biomes that allow visitors to experience Mediterranean and tropical climates within the county of Cornwall. The environmental conditions that influence the speed of photosynthesis within each biome were recorded and mapped to musical factors, thus creating two separate compositions. The installation then invited visitors to identify which piece of music they related with each biome in the anticipation that a positive outcome, in that they correctly identified the original stimulus, would support the mapping framework employed.

Following this introduction, a literature review explores the existing use of sonification - specifically, its function in an environmental context, and how the artistic license of defining mapping strategies can support science in helping people engage with strategic messages of vital and necessary action through a creative and artistic approach. Exploring how science and art interact can provide evidence to support the inclusion of the arts within our well-established STEM (science, technology, engineering and math) focus in education. To judge the value of our research to society it follows that we must consider the ethics associated with the drive for greater efficiency through use of computer algorithms, for example, or the empathy needed to support conclusions obtained through data analysis. It is through the arts and humanities that ethics and morality are explored and taught, becoming increasingly important within our spiralling advances in technology in order to question and regulate the approaches taken by tech giants and small start-ups alike. Following this, an overview of the sound design and desired compositional approaches to support the mapping framework will be explored and summarised. With clear intentions of the timbres and textures required for this project, the practice of artistic exploration has provided a set of sound classifications that have been defined for use within the sonification. For a project that looks to connect the environment and music, the use of synthesised sounds that model real instruments has been deployed in an attempt to keep the final sonification organic and natural in a way that abstract synthesised tones might not. To move beyond the direct mapping for audification, additional stochastic and generative methods have been explored to bring musicality into the sonification with the goal of having a less rigid composition that can be performed for many hours without obvious repetition. In looking to achieve a defined lack of repetition, there are key aspects of the sonification that will be designed to provide variation, from the subtle changes in the timbre of each sound to the patternless melodic structure of the auditory output. The construction of a system that supports the ability to define ranges of randomness and the density of impulses is central to this goal. A liability often posed regarding the value of sonification is that the sound modes can be perceived as monotonous after time and therefore become more of an irritation rather than a pleasurable and engaging way to perceive information. It is the hope and expectation that any potential for tedious repetition will be minimised through careful design of the sonification system. Having identified the sounds, and additional composition strategies for helping the sonification to maintain a degree of evolution, a practical-led approach to design will make use of the Arduino micro-controller and physical sensors to capture data before it is then sonified using the software programme Max. This chapter explains the data that will be captured in relation to the focus of environmental conditions that are pivotal to the rate of photosynthesis in plants. Having reviewed this approach, the following chapter will delve into the methodology for mapping the captured data to musical factors influenced through initial research into our associations of these factors against emotional responses. The use of the term *emotion* for the purpose of this study relates to an instinctive or intuitive feeling that has been established through past experiences. Having defined key factors, two surveys were undertaken to identify associations between musical factors - such as amplitude, pitch, tempo and harmony - to the rate of photosynthesis and, once outlined, the associations were revisited through an additional survey to confirm that the initial results have validity. Before the paper concludes, the details of the installation design are reviewed and some of the reactions analysed in an attempt to see if the strategies used ultimately proved to be successful. The project, in its initial consideration, proposed some key questions that this paper will look to explore and answer.

Questions:

- Is it possible to generate a sonification of environmental conditions by designing a methodology to create a meaningful mapping framework?
- What musical factors can be used to trigger specific emotions and which of these emotions do we associate with an environment that offers a higher rate or low rate of photosynthesis for plants?
- Can the sonification have meaning and therefore communicate information through the association to environmental conditions yet still offer generative possibilities and forever evolve - even with the same data set?
- What is the value of this research and how can it be developed?

Chapter 1 - Literature Review

1.1 Introduction

To design, construct, execute and explore this project, literary research investigating the field of sonification was essential in order to define the classifications and thus, establish a framework for the system of converting environmental conditions into sound. The *Sonification Handbook* (Hermann, Hunt, and Neuhoff, 2011) offers perhaps the most comprehensive overview on the theory of sonification and is the key text defining the techniques used to deliver the most effective transformation in anticipation of extracting information. To understand how these classifications can be used effectively, a review of sonification projects highlights the interdisciplinary nature of this field of research which combines science and art – and, how they can mutually benefit each other.

1.2 Sonification

The desire to explore physical quantities through sound undoubtedly can be justified once the power of the human auditory system is understood. This physiological system is highly complex, yet requires very little conscious effort and can continue to process information even during sleep. Although the data stream is significantly reduced, the processing of sound continues within the brain, ensuring that the mind is perpetually listening to the environment around us (Conenen, 2010). The power of auditory recognition is developed whilst in the womb and once born, "infants detect patterns or similarities in language" (Schlinger, 2010) before they understand the meaning of the words themselves. The acquisition of sophisticated meanings from language is well researched and Kuhl (2000) highlights this learning in two ways: 'discriminative ability' and 'statistical learning'. Straight from birth, infants can correctly distinguish their own mother from another woman without physically seeing either of them: a process of "incidental language learning" (Saffren et al., 1997). This detection of similarities within language is part of the discriminative ability suggested by Kuhl (2000) whereby, through this classification and selective recognition of sounds, it is possible to distinguish between the instruments of an orchestra or the voices on a bus. These learnt differences in timbre can be exploited when composing music to communicate a message that is not directly expressed which, for this paper, will be referred to as the conveyance of *meaning,* and research highlights how emotional connections have been developed through evolution and life experience to associate with musical factors (Juslin and Sloboda, 2006). Therefore, the process of creating an audio display – sound graph for data representation – can not only convey information allowing us to distinguish between the numerical values of data but, through a carefully measured mapping framework, it is perhaps possible to suggest emotional associations to quantitative data. This powerful listening process, which allows the identification of sounds, is primarily a process of pattern recognition and is generally undertaken with little or no concern for the immense complexity of the procedure.

Sonification is central to the development of an auditory display and was introduced principally by William Buxton at the CHI (Computer-Human Interfacing) conference in 1989 (Dubus and Bresin, 2013). Having formally introduced the concept of sonification in the 1990s, the definition for its purpose has changed during the last 25 years, with researchers at the International Conference on Auditory Display agreeing on and publishing the most recent working definition in the National Science Foundation's Sonification Report (Kramer et al, 1997):

> *''Sonification is defined as the use of nonspeech audio to convey information. More specifically, sonification is the transformation of data relations into perceived relations in an acoustic signal for the purposes of facilitating communication or interpretation.''*

Importantly, while this definition highlights three key factors of the sonification process, the use of spoken word is not considered within the classification. Sonification has the primary goal of conveying information and this is achieved through the conversion of specific data values, their numeric correlations and associations, into an audible signal that will be within the domain of human hearing; occupying a frequency range of between 20 Hertz and 20,0000 Hertz. This use of sonification has significantly developed since the initial notion was originally proposed and it is as much exercised with purely artistic intentions as it is with the goal of scientific analysis. With a discipline that is still establishing itself, as classifications of sonification are discussed and revised, the conveyance of information is fundamental to the definition. To communicate effectively there needs to be flexibility in the process of sonification and allowances given for choices made by the artist. Exploiting the additional knowledge of audio control and manipulation can enhance the communication of data, resulting in a more effective and engaging sonification. If the central objective is conveying information, then there is the argument that being data-driven forms the core of the sonification method, but it may be modified through artistic expression within the classification (Scaletti, 1994).

For composers of electro-acoustic and electronic music, reviewing the various categories of sound art is crucial to understanding the frameworks and theoretical guidelines by which the classifications of compositions are determined. It is simply not enough to state that 'conveying information' is the criterion by which a classification can be attributed as it can be argued that the purpose of Schafer's work was to highlight how humans are dramatically changing the sonic landscape of Earth. Within his 1977 publication, *The Tuning of the World*; this message was fundamental to his creations and Schafer went on to establish the World Soundscape Project (WSP). It was Schafer who coined the term soundscape in reference to the sound of the landscape but the term is most often used in colloquial language to define the component sounds of music. For Schafer, a soundscape conveys information about the environment and features themes that can be defined as "keynote sounds, signals and soundmarks" (Schafer, 1997). It is within the definition of *keynote* that Schafer (1997) refers to this fundamental component of the composition as "the note that identifies the key or tonality of a particular composition", equating this to the geography and climate of an environment. Whereas a sonification is organised and underpinned by numerical data, a soundscape is similarly anchored by the keynote, but both are designed to aid in communicating information through acoustic signals. Schafer's aim was to ensure an indissoluble connection between the soundscape and its geographical location through acoustic recordings, the sound is inherently synonymous with its physical origin. *Soundscape Vancouver* (1973) is a collection of soundscapes edited by Schafer that demonstrated this core fundamentalism but, ironically, can be listened to anywhere given the portable medium. This is somewhat akin to the contrasting viewpoint for recorded audio to create a disconnection of the sound from its environment and the significance of the "Sound Object"- an idea and style of electro-acoustic composition pioneered by Pierre Schaeffer in an attempt to "reduce" the sound signal from its original source (Schaeffer, 2013). This was not intended to fool the listener into misinterpretation of the sound object but to allow a form of listening that asks the audience to consider "not the external reference of the sound…but the perception itself" (Cox and Warner, 2013). For sonifications, it is this perception of the sound which is vital, not the tool or instrument used to generate it, although, it is difficult to say with total confidence that the choice of sound is not without influence in some capacity. Specifically, it is the movement and development of sound and the relationship between streams of audio that has particular significance to the origins of the source. For sonification to offer value for the listener there needs to be an equivalent of the *keynote* proposed by Schaeffer. A bedrock, consisting of control tone offering an initial pitch or amplitude, is needed if a relationship is to be perceived from a singular value. Alternatively, if consistently fluctuating values are required to be interpreted, then a period of listening is required in order to recognise where the boundaries of the sonification lie; a graphical display with show the ranges within the axis so that a visual understanding of minimum and maximum values can be quickly perceived.

Understanding the purpose of the sonification aids in the construction of the system and offers an insight into how the audio display is intended to be consumed. In order to outline the various methods by which the classification of sonification can be applied, researchers within the field have created a taxonomy for the methods applied: audification, auditory icons, earcons, parameter mapping sonification and model-based sonification (Hermann et al, 2011). Defining these categories reveals the goal of sonification across various disciplines, assisting in the contextualization of purpose as well as understanding the origins of this multidisciplinary method. *Audification* is the precise reproduction of data streams within the audio domain, explicitly, with the minimum amount of processing possible to convert the data into the audible range. Dombois and Eckel, (2011) offer the definition:

"*Audification is a technique of making sense of data by interpreting any kind of one-dimensional signal (or of a two-dimensional signal-like data set) as amplitude over time and playing it back on a loudspeaker for the purpose of listening"*

Dombois and Eckel (2011) argue that audio recordings, *sound recording data,* are included within their definition of the audification category along with *general acoustic data, physical data* and *abstract data*. This is a reasonable classification as the digital-to-analogue convertor is a direct transformation of data, a binary stream representing amplitude over time, delivered at a constant speed, to translate a switch with two states into sound. The recording of sound and control of playback parameters allows the captured data to be closely inspected; an extensive increase in the amplitude of low-level recordings can reveal microscopic details that would be missed by the threshold of human hearing. Also, the adjustment of temporal control allows for frequency shifting, rendering frequencies that were previously outside the audible range into the perceivable range of human hearing. Audification within *general acoustic data* can be observed each time a performer strikes the string of an acoustic guitar. The mechanical to acoustic conversion is perhaps the simplest example of audification and the stethoscope design of 1940, originally invented by Laennac in 1816, is still used in medical practice today (Dubus and Bresin, 2013). *Physical data,* such as electromagnetic waves, can be converted into sound and this category helps us hear data that, initially, lacks acoustic familiarity. MAARBLE (2017) presented *Sounds of Space,* a collection of compositions created from the radio waves that are generated naturally within the Earth's atmosphere. Using a Very Low Frequency transmitter (VLF) these waves are brought into the audible range. "These sounds correspond to several types of radio emissions propagating in the Earth's atmosphere, ionosphere and magnetosphere, inviting people to "feel" the science and to think about art." (MAARBLE, 2017). This use of audification provides an alternative insight into the frequency differences between radio waves and just as The Photosynthesiser aims to help people *hear* their environment in an alternative way, initiating discussions about the volatile nature of our climate. Finally, *abstract data* can be much harder to quantify for sonification through physical sensors as it is within a virtual domain. The fluctuations of stock markets shares and use of audification to monitor patterns is an example of where this type of data sonification is used and exploited to expose more efficient ways of processing data streams within human comprehension. Nesbitt and Barrass (2004) developed a multi-sensor interface, by using both visual and auditory displays, helping to maximise the human-computer interfacing bandwidth. This use of a multi-sensor display enabled users to predict movements of upwards trends with greater accuracy and tests showed that audio alone was more successful in the downward trends, predicting correctly between 80% and 100% of the time. This enhancement of traditional displays for data analysis highlights the value of sonification and the power of the human auditory system to interpret multiple frequencies and amplitudes subconsciously. There are opportunities within the system design of *The Photosynthesiser* to allow for hands-free monitoring of conditions vital to plant growth through audification. Although the human hearing system is extremely sensitive, mapping the levels of physical sensors to frequency generators, in-line with the categories of audification, would not be sufficient to set indicators for the deterioration of conditions; this would require addition categorisation or auditory icons and earcons to alert users to drop-offs at pre-determined thresholds.

Auditory Icons grew out of the personal computer developments in the 1980s and were specifically developed by Bill Gaver, investigating the use of sounds within the desktop interface. Gaver (1986) suggested that “Auditory icons provide a natural way to represent dimensional data as well as conceptual objects in a computer system”. Supporting virtual actions undertaken within the desktop interface with sounds familiar in everyday life helped to reinforce the illusion of interaction with a “real” object. Brazil & Fernstrom (2011) specify that “the most complex and expressive forms of auditory icons move the sound into the domain of interactive sonification where a continuous representation is possible, allowing complex user gestures and processes to be displayed”. This interaction is a very powerful form of sonification and can help those with visual impairment understand more about their physical surroundings or virtual actions within a computer interface. The fundamental concept here is that auditory icons have a direct relationship to the environment, providing meaning through the playback of either directly sampled or physically modelled sounds awarding feedback for user’s interactions with the computer interface. When the sound’s meaning is not the purpose of design, and the sonification is one of notification rather than an existing relationship, the classification is that of *Earcons*. For earcons, the meaning of the sound must first be learnt, much like the instructions relayed by bugle calls to American soldiers in battles during the 19th century (McGookin and Brewster, 2011). The use of earcons is widespread but the majority of everyday experience within this classification is primarily that of computer systems and more recently mobile and handheld devices. Research into the value of the auditory notification and categorisation of earcons was proposed by Blattner et al., (1989) on the development of auditory warning research within medical equipment, initially proposed by Patterson et al., (1986) and an expansion of the seven conditions proposed by Marcus (1984) in *corporate identity for iconic interface design*. The central concept to the definition of earcons by Blattner et al., was the use of motifs within the compositional design that, once learnt, allowed for instantly recognisable and individualistic association with computational processes. The use of musical motif to develop learned association, and therefore provide a distinct message from an auditory trigger, is now extremely commonplace within digital media, used from company branding through to character association in film and television. In reviewing the categories of sonification the definitive purpose of each class becomes distinct and an analysis of the suitability of audification, auditory icons and earcons highlights that, although applicable in certain circumstances, they are not the right model for *The Photosynthesiser*. The direct transformation of data will not allow for enough melodic movement within the sonification to be meaningful to the listener, the lack of interaction with the system removes auditory icons and although there could be a use for an alert system, if the purpose of the sonification was to monitor conditions, it is not relevant to the research project at this stage.

The fourth category of sonification, *parameter mapping sonification* or PMSon makes use of the multi-dimensional properties of sound to allow for numerous data streams, if required, to be transformed into meaningful sonifications (Grond and Berger, 2011). Although an early, general definition of the term sonification was proposed by Bly (1994) to be “audio representation of multivariate data” but, as the discipline has developed, this definition is now most suited to the classification of PSMSon.

Whether the data is physical or abstract does not matter within the classification: it is the scaling of relationships between the data domain and signal domain that separates PMSon from the previous sonification categories. The tuning of this mapping system is integral to the design process and, in order for the sonification to offer a meaningful auditory display for end-users, the intended interpretation of the data must be considered. As Ground and Berger (2011) highlight "Effective PMSon often involves some compromise between *intuitive*, *pleasant*, and *precise* display characteristics" and the flow map, created by Groud and Berger (2011) for a *general design process,* breaks the development into three discreet sections: data features, mapping function and sound synthesis. Analysing and categorising the data being used for the sonification requires decisions to be made regarding the number of channels the data will occupy as well as the range - and, whether the data will be read as a continuous stream or individual values sent at either intermittent or regular intervals. Dubus and Bresin (2013) say of parameter mapping "it allows for a much greater flexibility… the design of each mapping should, in return, be considered very carefully: an unfortunate choice can dramatically affect the usability of the whole system." For sonifications to be intuitive, some standardisation of the mapping strategies for physical or abstract quantities against sound parameters could be established, so that users can quickly identify associations between these two domains. Research by Dubus and Bresin (2013) provides an overview of mapping strategies used in over 700 sonifications and concludes that pitch is by far the most common sound parameter used but rarely is the efficiency of this auditory dimension evaluated.

The final category of sonification is *model-based sonification* (MBS) and was originally introduced by Herman and Ritter (1999) as a more organic and intelligent system of audio feedback generation as a result of interaction with the model. In looking to develop computer interfaces beyond the standard approach of visual display priority, Herman and Ritter (1999) state that MBS "demands the creation of *processes* that involve the data in a systematic way, and that are capable of evolving in time to generate an acoustic signal", much as a physical modelling synthesis will determine a set of resonant filters that, once triggered, will produce a consistent timbre or spectral output. This is defined somewhat by the initial excitation source and the frequency content within, as well as by the force and object used to animate the model. Much like a musician can explore the timbral boundaries of their instrument through various approaches to the excitation of the string, reed, membrane etc. MBS allows the user to explore data through equivalent mechanisms where the sonification is not a one-dimensional feed forward approach but relies on interaction between the operator and the system (Wöllner, 2017). Through MBS, the operator is searching for specific meanings, much in the same way one might tap on a wall to understand something of its properties – for example, whether it is hollow or solid. This allows for much more meaningful and efficient exploration of data through acoustic associations that are intuitively recognised through our own experience of active and passive sound information in everyday life (Dias, Courty and Kamp, 2009) (Herman, 2011). As this MBS technique is relatively new in comparison to the others discussed, through further testing against the other classifications, it may well become the preferred approach for data exploration and artistic creation. The categories of sonification reviewed here: audification, auditory icons, earcons, parameter mapping sonification and model-based sonification, can be classified into groups of: Discrete Data Representations, Continuous Data Representations and Interactive Data Representations (Worrall, 2007). Discrete Data refers to auditory icons and earcons where every data value is directly sonified. Continuous Data Representation (CDR) becomes useful for data sets of immense quantity and with temporal significance. Audification and Parameter Mapping would fall within this category and - in respect of the proposed purpose of this project – would be the best suited classification to work within. Future developments of this project might then force a change to the categorisation with the installation becoming interactive, allowing for manipulation of the model to demonstrate environmental change, should the conditions of our planet become more unstable. This would move into the category of Interactive Data Representations and could aid in strengthening our understanding of the sonification's conveyance of information, once we can engage on more than just a passive level through live manipulation of the data.

Ultimately, it is the value of the final artefact which is of utmost importance to both scientists and artists. Developing knowledge or aiding in the perception of new meaning is the goal to be attained from listening to data-driven sonifications or, alternatively, the exposure to 'data music' can draw an emotional response from the listener, ultimately leading to behavioural change. The emotional impact of listening to music derived from datasets is highlighted by Andrea Polli (2016) as the primary motivation for her work with sonifications. Polli's work intersects between science and art and, through this interdisciplinary philosophy, endeavours to engage and inform the public on environmental issues. Where it can be difficult to emotionally connect with the concerns of climate change from observing numerical models, the translation of this data into sound enables artists like Polli to play with the expressive nature of music in an attempt to engage the public. She has worked closely with NASA and the Goddard Institute Climate Research Group creating sonifications of atmospheric models predicting temperature rises in New York City. Polli works with the expressive nature of music to convey meaning within the sonification; "as you listen to the compositions, you will travel forward in time at an accelerated pace and experience an intensification of heat in sound". By using a fairly simple mapping framework that multiplies both pitch and amplitude, as the average temperature increases within the models, Polli is able to create an auditory experience that has a direct relation to the escalation of heat intensity. As amplitude is directly related to the intensity of sound, measured by the power per square meter, and heat transfer is measured as an intensity of radiation, distribution of radiant heat flux per unit area, there is a direct physical correlation between these two parameters. In order to justify the extension of such a sonification, designing a system that connects with the listener on a meaningful level so that they are able to make associations between the two compositions and the environments they derive from, is fundamental to the mapping process. This philosophy, to enhanced awareness of scientific and social issues through emotional connection, is pivotal to the concept of *The Photosynthesiser*. It is within the audio information design process of mapping data to musical parameters that the influence of emotional responses to music performs an important role within the sonification.

1.3 The Art of Science through Sonification

Mathematics is at the heart of all science and provides the foundation on which science study programmes are based. It is a general resource used by scientists and a language that was first constructed through interpretations of number, magnitude and form by hunter-gatherers over 20,000 years ago (Boyer and Merzbach, 2011). Engagement with art has been observed within every discovered culture on this planet and the emotional activities associated with dance, music, drama and visual arts are central to human existence and evolution (Sousa and Pilecki, 2013). Both of these approaches are human beings' endeavours to understand and describe their surroundings; artists and scientists are perpetually making observations from different perspectives to perceive new meaning or to gain a greater understanding – then, disseminating their findings to others. Although in modern education, these two disciplines are deemed to be polar opposites; science is objective, analytical and useful, art is subjective, sensual and frivolous (Sousa and Pilecki, 2013). This separation is not healthy for a balanced examination of problems and the development of solutions in the modern world. The two opposed approaches are in fact harmonise with each other. Art and science coexist within the inquisitive nature of human beings and require the function of both curiosity and play (Lionnais, 1969). Both factors are extremely relevant to scientists and artists, as well as the educators, who cite play as "a highly effective means of accelerating learning" (Nicholson, 2016) and Greenberg (2000) states "curiosity drives play and play feeds on curiosity". Although the method for exploration and discovery is founded upon the same principles the cognitive approach can differ. However, mathematicians will often talk about the *beauty* of mathematics, the pleasing aesthetics of the form: a use of terminology extremely familiar to artists.

> "*A mathematician, like a painter or a poet, is a maker of patterns. ... The mathematician's patterns, like the painter's or the poet's, must be beautiful; the ideas, like the colours or the words, must fit together in a harmonious way. Beauty is the first test: there is no permanent place in the world for ugly mathematics*." (Hardy, 2016)

Leonardo Da Vinci, one of the most celebrated artists of the Renaissance, clearly found no need to separate these two disciplines but instead used one to inform the other. His drawings are examples of empirical science and wonders of art, inclusively. In the 15th and 16th centuries this separation was not necessary or even considered but, within modern culture, the two fields are segregated. This is most obvious in the curriculum-based initiative STEM, an acronym for Science, Technology, Engineering and Maths. Where this focus would at the outset seem like a functional approach to meeting workforce demands, scientists, mathematicians and engineers agree that the skills and tools used in formulating approaches to problem-solving and team research lie within the arts. Sousa and Pilecki (2013) suggest that the followings skills are not taught as part of STEM courses but find their place within the arts:

- *Draw on curiosity*
- *Observe accurately*
- *Perceive an object in a different form*
- *Construct new meaning and express one's observations accurately*
- *Work effectively with others*
- *Think spatially (How does an object move when I rotate my head?).*
- *Perceive kinaesthetically (How does it move?).*

Although these skills might be represented within a selection of STEM courses currently, it is certainly not the case for all and The State University of New York, along with others, are redesigning their curriculum to offer interdisciplinary programmes intended to foster creativity by combining arts and humanities within STEM subjects (Madden et al., 2013). Jemison (2002), an astronaut, a doctor, an art collector and a dancer is clear about this underpinning connection between art and science stating that they are "manifestations of the same thing. The arts and sciences are avatars of human creativity". Instead of the traditional approach to education, with the intense focus on subjects based around reductionism, the need to include chaos and the opportunity to develop a non-linear approach to education has become far more important, specifically, with the rapid evolution of our society due to the extreme developments in global connectivity and interaction (Boy, 2013a). Steve Jobs famously said of his company's staff "We are artists, not engineers" (Gallo, 2010). This holistic approach to system design is paramount to the study of computer music and a pivotal consideration within the construction of *The Photosynthesiser* installation. To study computer music one must be both a scientist and an artist. To design an algorithm that produces musical output that is appealing, requiring people to engage with the listening process for a sustained period of time, requires technical knowledge and creative understanding in equal measure. It would be quicker to create the algorithm with the goal of musical output as the only design objective but to test and observe from subjective viewpoints, positioning oneself in the eyes of the listener, obtaining qualitative data and adjusting the code, requires an artistic and creative skillset. Boy (2013b) argues that companies who work within the technology-centred design, focusing on short-time fixes and event-driven models, are leading us down a design route void of human consideration. The main drive of these actions is financial and is somewhat understandable from a business perspective but if this is to become the primary motivation for system design we will soon find our technology less appealing and functional. As Winston Churchill pointed out:

> "*Young people at universities study to achieve knowledge and not to learn a trade. We must all learn to support ourselves, but we must also learn how to live. We need a lot of engineers in the modern world but we do not want a world of modern engineers" (Churchill, 1948 cited in Boy, 2013b p.2).*

Churchill supported the idea that the single discipline approach to design is not ideal and the need to work across disciplines is essential to ensuring a more universal methodology to cope with our socio-technical environment.

It can be argued that STEM alone cannot connect with the world as effectively as when the arts are included and therefore greater emphasis should be placed on a human-centred design approach (Boy, 2013a, Maguire, 2001). Science can prove that we need a behavioural change in society through investigation of environmental issues - melting ice caps or examination of the plastic content of our oceans - they are not, however, always best placed to present this information. The dissemination of statistics based on research with negative imagery of potential consequences is not the most effective approach (James, 2010). This is not to say that facts do not matter - they do. In a survey of six countries it was demonstrated that an enhanced understanding of the causes of climate change leads to an increase in concern for the consequences (Shi et al., 2016), as well as other studies that recognise explanation can reduce bias (Ranney and Clark, 2016) and political separation (Johnson, 2017). The traditional deficit-model for communication of scientific research is well established and there is certainly an appetite for the factual propagation of findings across the general public (Cheng, 2010). This is not to say that it is the right way to engage everyone. In a survey of scientific communication models, Trench (2008) highlights that a range of approaches is most effective in understanding public opinion and their diverse needs and views on topics in order to encourage conversation, leading to participation and engagement with the research agenda. Einsiedel (2000) supports this, stating that the *cognitive deficit model* and *interactive science model* used in conjuncture can "contribute to the ongoing discussions about the public and science... these frameworks may be complementary rather than mutually exclusive". Scientists are now more willing to work alongside artists to help engage the public. As a creative solution to raise awareness of the destruction of over 15,000 chestnut trees in Berlin, BBDO, an advertising agency in Germany, created a sound and light installation around a 100-year-old chestnut tree in the city. Each time a chestnut fell it would land on a canvas triggering a coloured light wash and a musical tone. This project, in collaboration with BUND (Friends of the Earth Germany), was advertised as a unique charity concert and donations for the preservation of trees increased 800% while the installation was active, compared to an average month. SMS donors received a "thank you" from the tree, factual information on the benefits of tree preservation within the city and a music composition sent out as an MP3 (Macleod, 2013). This installation provides the perfect combination of interactive and deficit models for scientific communication.

The incorporation of methods for content delivery is commonplace within education incorporating the various proposed learning styles of students. Students are informed that they have a preferred learning style, however, some research would suggest that this is a misconception (Walsh, 2007). Differentiation of learning modalities is often cited for students and they are assessed for a preferred approach to learning: auditory, visual or kinaesthetic. The reality is, if presented with a combination of all three, the student will have multiple pathways for memory recall and therefore greater chance of retention and recollection. As Land (2013) highlights, “integrating the arts into core content areas not only enables students to explore a single concept from different vantage points, but it also utilizes all the different modalities of learning previously mentioned, both leading to the formation of more neural pathway”. This is typified by the sonification of environmental data within *The Photosynthesiser* and offers visitors an additional perspective on the variation in conditions between the two biomes. It is the artistic interpretation of the numeric data that can help engage the public and encourage discussions, gaining new understanding and finally, influencing behaviour. The presentation of scientific data through artistic conceptualisation can be further enhanced if the emotional connection to the work is considered as part of the design model. For the sonification process of *The Photosynthesiser*, understanding how musical factors relate to emotional triggers has influenced the mapping framework and musicality of the final installation.

Chapter 2 – Compositional Algorithms

2.1 Introduction

Sonification offers an opportunity to move beyond the direct audification of data and creatively expand the system to work not only as an audio display but a piece of sound art as well. The intention to create music that can be pleasant for prolonged periods and still be precise in its delivery of information is at the forefront of the system design. Delivering on these objects requires consideration for the textures and timbres to be used as well as the composition construct. To achieve a deep level of control over the system practice-led research into the programming environment of Cycling ‘74’s Max platform reveals near endless possibilities for sound design and algorithmic compositional techniques. Ensuring that a sonification's musical output can be played continuously and maintain variation, even if presented with repetitive data, requires a degree of controllable randomness. Cipriani and Giri (2009, 2013) outline many possibilities for sound design and compositional techniques for Max which sit as the underpinning to the practical research within this chapter.

2.2 Sound Design

To provide a sonic landscape that represents the data sources collected, the use of physical modelling synthesis, specifically modal techniques, have been used to generate timbres and textures that are to analogous to natural sound. As the sonification is anchored in data harvested from the natural world, implementation of physical modelling offers timbres that provide a sense of traditional instrumentation with the intention of feeling harmonious with the project's intrinsic relationship to nature. Each sound is defined by the instruments geometrical and material parameters outputting a natural character as opposed to that of a synthesised sine wave which, although defined as the building block of all sound, does not exist as a pure tone within the natural world. The decision to work outside of equal-temperament tuning was primarily an artistic decision. The requirement of the audience to engage with the fluidity of the sonification and to hear it not as an everyday musical composition but as a piece of sonic art, making the listener more likely to question and analyse its concept and construction rather than fixating on a repeatable melody assuming their normal listening mode. Physical modelling is based on the sound reproduction characteristics of real instruments as opposed to the other methods of synthesis such as additive, subtractive and FM, which can often disregard the attributes that contribute to the construction of the imitation in favour of focusing on the output signal. As Roads (1996) highlights, the purpose of physical modelling can be both scientific and creative, matching the key theme of *The Photosynthesiser* project. To describe the sounds created for this project as physical modelling synthesis would not be entirely true. The techniques used were specifically modal synthesis, a type of physical modelling using resonant filters to simulate the construct of the instrument. The usual classification of instrument that lends itself to model synthesis is one that is physically struck upon the resonator, for example, bells, chimes, cymbals or blocks. These, as a class of instrument, are referred to as *idiophone,* specifically *concussion idiophone.* Idiophone is defined as "any musical instrument that produces sound by the vibration of its own material" (Randel, 2003). This is in direct contrast to instruments that rely on a string, membrane or a column structure to generate and amplify oscillations. The concussion category of idiophone refers to the way that the material is struck with another sonorous object; in the case of a cymbal used in popular western music, this would primarily be a wooden stick but also be a variety of other materials including felt, plastic and steel. In considering the sound design, the use of chimes, bells and gongs were selected as suitable timbres as they would be more suited to a composition using microtones rather than the traditional Western tuning of twelve equals tones per octave.

The development of the sounds used in the project were constructed using Cycling '74's Max 7. Max is a programming environment that allows the user to graphically connect objects with patch chords to design and construct near limitless sound and audio processing possibilities. The advantage of such software is that there are no limits imposed from the outset by the software, in that, you are given a blank canvas with which to build your desired patch. There are other software options that offer similar control and freedom such as Pure Data and SuperCollider but these were not considered for this project as there has been considerable time investment in Max from the onset of this process. Max is also flexible enough to communicate with external hardware and therefore made it a logical choice for the data collection from the Arduino microcontroller and connected physical sensors. The creation of patches for this project was researched from Max's in-built tutorial system, *Electronic Music and Sound Design Volumes 1 and 2* (Cipriani and Giri, 2009 & 2013) and *DaveBessellMusic* (Bessell, 2018). These were altered, expanded and developed to work within the required goals of *The Photosynthesiser* project. For the final instillation, the sonification was constructed from six sounds that were influenced by the captured data of the Biomes inside the Eden Project. The classification names given to the sounds were named without always resembling the sound described. The names given to the sounds were: *Gong, Metallic Hit, Bell, Chime, Drone, Wind*.

The *Gong* (Appendix 1. i) was based around the use of a band-limited random signal generator at 300Hz passed through multiple resonant bandpass filters using the *poly~* object (Cipriani, Maurizio, 2013). The *poly~* object was the primary aspect of this patch as it allows for many instances of the resonant body to run simultaneously. For this particular patch, twenty instances were used to generate the final sound and were designed to ensure variation of the output timbre due to the random nature of the frequency and duration input parameters. The *Metallic Hit* (Appendix 1. ii) was of a similar construction although the instead of the *poly~* object the *fffb~*, a fast-fixed filter bank similar to a resonant bandpass filter was used. This was constructed to allow for eight filters to be simultaneously triggered. For both of these patches, the parameters selected that were to be manipulated from the data collected within the biomes at The Eden Project, were the density of strikes and the overall output amplitude. The *Bell* (Appendix 1. iii) was derived from pink noise patched through eight resonant bandpass filters and four comb filters in parallel, all routed through one final bandpass filter with a centre frequency of 634Hz. Rather than using the response time of the filter in relation to the filter's Q or bandwidth, a *function* object was used to provide an amplitude envelope for each of the filters. The *Gong, Metallic Hit and Chime* are similarly constructed and rely on parallel bandpass filters to create tonal shaping for the modelling of each sound (Creasey, 2017). By sending an impulse signal containing a single sample of all frequencies, at a high amplitude through the filters, it is possible to increase the Q value to such an extent that the filters start to resonant. The Q factor also defines the duration or response time (Zumbahlen, 2018). To allow for alterations within the composition, the chance of the bell strike being triggered was used as a variation control. The *Chime* (Appendix 1. iv) was derived from the same use of resonant bandpass filter but this example was based around a band limited random signal generator at 1000Hz (Cipriani, Maurizio, 2013) but altered to provide scope for the gain, frequency, Q to be affected by incoming data. The patch was further developed to include the integration of portamento as the variations in pitch increase, due to changes in the data input.

One considered purpose of the sound design is to play upon the sense of familiarity then, through synthesis modulation, develop the sound from a recognisable source into something otherworldly. It is hoped that the sounds will initially engage the listener then, through manipulation, portray the unnatural characteristics of hearing such a sonification and assist the audience in realising the relationship between the physical world and the composition. The proposal of an area of uncertainty, in timbral recognition within the realm of physical modelling, has been outlined by Dr Bessell (2011) in his paper *Ophidian and the Uncanny Valley*. Here Bessell suggests that the original theory of Dr Mori's 'Uncanny Valley' (1970), which relates a human's emotional response to realism of robot behaviour and appearance, can be associated with the psychological domain of instrument recognition. This anthropomorphism of robots and emotional relationship to humans begins to deteriorate, as the robot becomes close to but not quite human-like. There is a similar proposed drop in the familiarity of sound classification when the physical model used, begins to morph into a new classification but retains some key properties that allow us to make a psychological connection between timbre and the physical instrument. It is the hope of the composer that some of these areas of uncertainty will be presented as part of the sound design within the sonification. Chimes and metallic resonances have been used as their inharmonic content provides a less uniformed sonic structure than other classifications of instruments (Deutsch, 1982, pp.2). The slightly chaotic combination of partials will aid in the use of non-chromatic melody as, although they still maintain a fundamental frequency, this uneven distribution of frequencies will be in line with the changing pitches of note distribution. To design this classification of sounds, resonant band pass filters have been used, with extremely narrow pass bands and high amplitude gains. Compiling an array of filters and assigning them to integer and non-integer frequencies, realistic bell and chime like tones have been created. In an attempt to relate the audio to the data source, the sound design has been crafted to provide a conscious sense of atmosphere within the listening experience. The chaotic nature of frequency dynamics in atmospheric wind is similar to that of pink noise (Voss and Clarke, 1978). Band pass filtering noise and then changing the frequency of filter, provides a broad simulation of wind. By boosting and attenuating the frequency and gain parameters, it is possible to generate a sense of movement within the constant drone. To provide a sense of space and depth within the sonification reverberation has been applied sparingly to each sound and a little delay on the *Gong*.

2.3 Generative Composition

The rhythm and melody are generated through algorithmic processes that have been designed to be on the cusp of random but allowing for control of some parameters at the discretion of the performer. This interaction and manipulation of algorithmic systems can be associated with the current trend of a classification called 'generative music' (Collins and Brown, 2009). There are many descriptions of compositional methods that relate to the world of automated music generation. Ames (1987) reminds us that the workings of 'Push Button Bertha', whose first public performance was in 1956, demonstrated perhaps the first instances of an automated composition. The automatic method was based on a set of 6 rules, applied to an initial designated pitch in order to start the procedure. From this, a composition based on mathematical equations was generated. The word 'algorithmic' is defined as "a recursive procedure whereby an infinite sequence of terms can be generated" (Algorithmic, 2016). The set of rules was determined, and the compositional process would follow these equations precisely. In this example, there are set boundaries to which the algorithm must adhere and there is no room for probabilistic chance. This fixed computational task is defined as a *deterministic* algorithm (Roads, 1996). In opposition to this, *stochastic* algorithms allow for random choice and work on a comparison of probabilistic chance for values (Roads, 1996). Iannis Xenakis used stochastic algorithms to create the musical material with his '*stochastic music program'* in 1962 (Ames, 1986). Within this programme, Xenakis would define the maximum and the minimum number of notes each instrument could play per second. The programme could convert these values into logarithmic densities (from 0 to 6) for each of the points within the scale, then refer to a probabilistic range to select the instrument by way of timbre. The technique of stochastic algorithms has been applied to the rhythmical density of the chimes, within this sonification. The probabilistic chance of the chime model triggering is defined through a Max patch based on the random impulse generator designed by James McCartney. This random generation is itself based on probability, which in this case is defined as density. The chance of triggering impulses is increased as the temperature data amplifies, creating a complex spectrum of inharmonic sound that represents the high level of energy activity in the photosynthesis process. The algorithms that provide the trigger mechanisms for the rhythmic parts of the composition also drive the melodic sequence. The composer can define specific pitches to be used but the order in which they play is not at the composer's discretion. This process could be defined as *computer-aided algorithmic composition* (CAAC). Fernandez and Vico, (2013) state that the differentiation between CAAC and algorithmic composition, when looking at two processes at their extremes, is not exactly clear. CAAC offers a low degree of automation and algorithmic composition a high degree, but they are synonymous with one another, as CAAC systems can be developed to include complex automation of parameters.

The goal of *The Photosynthesiser* was to create a composition which constantly evolved and didn't repeat even when presented with repetitive data sets. The sonification of data needed to be meaningful through the transmission of information and, therefore, should relate to the selected data streams by representing variations and those be audible in order to hear significant fluctuations in the environment's data output. Having defined the sound design parameters, a system that connected the various elements of this network was designed to allow each part to communicate and produce a generative mechanism for the sonification. Steve Reich's 1965 composition "It's Gonna Rain" has been cited as being a key influence on Brian Eno and his interest in developing generative music (Wilson, 2015). Reich's composition was composed using a system of two tape recorders which ran at slightly different speeds but played the same piece of recorded audio. The result was a continuously evolving soundscape that was the result of the system mechanics. Reich (1968) notes that "*Though I may have the pleasure of discovering musical processes and composing the musical material to run through them, once the process is set up and loaded it runs by itself*". Although this provides a generative method for music composition it is still a method in that every time the system is started the same piece of music is heard. The goal of *The Photosynthesiser* is to create a generative product so that every time the system is activated, even if the same data sets are used, the musical output is slightly different. The key objective for system design is that once the sounds are formed and the mapping framework established, the installation will run by itself, continuously, without obvious repetition in the form of melodic phrasing and still provide two different compositions that can be understood to represent each biome at The Eden Project. This is a development of Reich's "It's Gonna Rain" but similar in concept to Terry Riley's system design for "In C", a composition expressed as a set of principles and procedures through which the performers dictate the arrangement (Carl, 2009). Pivotal in the creation of a generative system is the use of randomness and allowing the system to make arbitrary choices but within constraints set out by the composer or designer. John Cage was a visionary for the incorporation of chance within musical composition. By asking questions about what the music might do Cage was able to determine options that allowed for multiple possibilities thus removing himself from dictating or imposing his own preference on the composition (Holmes, 2002). Cage reflects that it is his desire to not hear the piece until it is being performed for the first time. With this in mind, the question of whether the sonification can have meaning and yet still offer generative possibilities, forever evolving even with the same data set, can be asked and in attempting to find out the data must first be defined.

Chapter 3 – Capturing Data for Parameter Mapping Sonification

3.1 Introduction

Designing a mapping system to sonify environmental conditions vital for photosynthesis in plants requires investigation in order to define this dataset and thus determine how this will be captured and stored. The utilisation of the Arduino open-source software and microcontroller hardware offered a cost-effective system to begin building a prototype. A long period of testing was required to discover whether the physical sensors, in conjunction with the Uno board, would capture and transmit this data, not only to the Arduino software for accurate translation of voltage into meaningful units for measurement purposes but also be accessible to Max for sonification. The Arduino forum provides a wealth of information for the programming enthusiast, enabling novices to begin coding with C/C++ language and use a range of predesigned sketches that can be loaded directly into the Arduino digital interface. The following chapter defines the data selected for this project, the way in which it was captured and reviews the final tables from each biome at The Eden Project.

3.2 Defining the data for photosynthesis

Photosynthesis is the method used by plants, blue-green algae and some bacteria, of storing light energy and using it to drive cellular processes (Blackenship, 2012). Hodson and Bryant (2012 pp.168) claim, “Photosynthesis is, in many respects, the most important process in the world”. Rubisco, contained in pigmented chloroplasts inside leaf cells, is an enzyme necessary to kick-start the process of carbon fixation in photosynthesis. Through this reaction, carbon dioxide is converted into energy-rich molecules such as starch, glucose, fructose and cytosol. By storing carbon, from which, indirectly, we obtain fossil fuel and by controlling atmospheric levels of carbon dioxide, which in excess levels has led to global warming (Kawahata and Awaya, 2006), we can see how this claim can be justified. Add to this the fact that one of the by-products of this process is the release of oxygen back into the atmosphere, it is evident that the necessity to maintain reforestation projects to combat the increasing levels of carbon dioxide (CO_2), are pivotal to the campaign against global warming (Johansen, 2002). To draw upon key elements of photosynthesis, capturing data related to the process is fundamental. Light intensity will be measured, as it is the main input source for collecting energy. A pigment in the plant called chlorophyll absorbs individual photons from the sun and catalyses the conversion of solar energy into chemical energy (Rebeiz, 2014), resulting in the highly energetic molecule: adenosine triphosphate (ATP) and also nicotinamide adenine dinucleotide phosphate hydrogen (NADPH). ATP provides chemical energy and NADPH acts as an electron donor. This light-dependent process also splits water (H_2O) into hydrogen and oxygen. The hydrogen is used to replenish electrons and the oxygen is released back into the atmosphere (Solomon et al. 2010, p.202). CO_2 is absorbed through openings on the upper and lower surfaces of the leaves called stomata (Kirkham, 2001, p.175). CO_2 combines with the ATP and NADPH to generate glucose, providing the plant with the nutrition needed to grow and flourish (Alters and Alters, 2003, p.113). This process is known as the *Calvin Cycle* and from these processes, we can define the following equation:

$$6\ CO_2 + 6\ H_2O + \text{Light Energy} \dashrightarrow C_6H_{12}O_6\ \text{(glucose)} + 6\ O_2$$

Temperature affects the enzymatically-catalysed reactions and therefore has an impact on how efficient the photosynthesis process is (Lambers et al. 1998). To provide a measurement of the water availability, a combination of two sensors have been utilised, one for moisture levels in the soil, the other for measuring relative humidity in the atmosphere. Soil moisture can be measured in different ways depending on the scientific discipline but, for the purpose of this investigation, it will be measured as the amount of water held in spaces between soil particles. The rate of photosynthesis is reduced as water availability in the soil decreases (Pallardy and Kozlowski, 2008, p. 147) but as numerous studies show, the decrease is very different across various categories of plants and trees (Upchurch et al. 1955). In spite of which, soil moisture plays a pivotal role in the photosynthesis process and was sampled as part of the data collection. In order for the plant to take in CO_2, the stomata are opened within the plant's leaves, the consequence of this is that water vapour exits through these openings; a process called transpiration (Bethell and Coppock, 2000, p. 62). If the plant is dehydrated each stoma will close to preserve water content and therefore significantly reduce the intake of CO_2 and the rate of photosynthesis will extensively diminish. Humidity also affects the rate at which plants can photosynthesise. As temperature increases within the atmosphere, the amount of water vapour that can be held in the air increases as well. This is because faster moving molecules of both air and water and if the water vapour molecules are moving quickly, it is harder for them to condense into liquid (Robertson, 2005, p. 74). As the amount of water content is comparative to temperature the measurement of relative humidity is used. If the relative humidity is measured as 60% at 25°C this means that each kilogram of air contains 60% of the maximum amount of water vapour it can hold at that temperature. As the temperature increase but the water content stays constant, the relative humidity percentage would drop (Yabuki, 2011, p.43). In a study of the effects of humidity on photosynthesis it was found that there was a direct correlation between a rise in humidity and a rise in photosynthesis rates (Rawson, Begg and Woodward, 1977). This reaction to atmospheric humidity levels is similar to that of water content; the greater the concentration of water in the air the less evaporation of water from the plant. This has a positive effect on the rate of photosynthesis as the plant can open the stomata wider to draw a high level of CO_2. In order to collect meaningful data related to the process of photosynthesis, sensors have been used to measure light, moisture, humidity, CO_2 and temperature, covering the key mechanisms.

3.3 Arduino and sensors

Barnard et al. (2014), discuss the application of an Arduino microcontroller to construct a device for logging photosynthetically active radiation (PAR). Their goal was to establish a means to take measurements of PAR, at low monetary cost, but with accurate results. For this research paper, the use of the Arduino Uno R3 (ATmega328p) presented the best solution due to the ease at which it can obtained and the nature of simple C and C++ coding needed to communicate with third-party sensors. It is possible to route data, from the Arduino software through to Cycling '74's Max 7 for processing and sonification. The *serial* object in Max can be used to send and receive data transmissions from serial ports. This object can be configured to specify Baud rate (data rate measured in bits per second) and the number of bits used for each pin. From this object, it is possible to differentiate the value of each pin of the Arduino Uno board. In order to collect data related to light, a photoresistor (VT90N2 LDR) has been used containing a photoconductive cell (VT900 Series) also connected to the Arduino board. The voltage output of the resistor rises as light intensity increases. A temperature sensor (TMP36) was used to provide a linear voltage output in relation to Celsius changes of ±1ºC. To provide readings of CO_2 levels, the Sandbox MG811 CO_2 sensor was preferred due to its high level of sensitivity. The output voltage decreases as the concentration of CO_2 increases. A non-branded moisture detector was used, providing a change in voltage output in relationship to the level of water detected upon the plate. Humidity was measured using a DHT-11 sensor, which contains a capacitive humidity sensor and a thermistor. It is possible to calculate the relative humidity by diving the density of water vapour by the density of water vapour at saturation. The DHT-11 detects water vapour by measuring the electrical resistance between two electrodes.

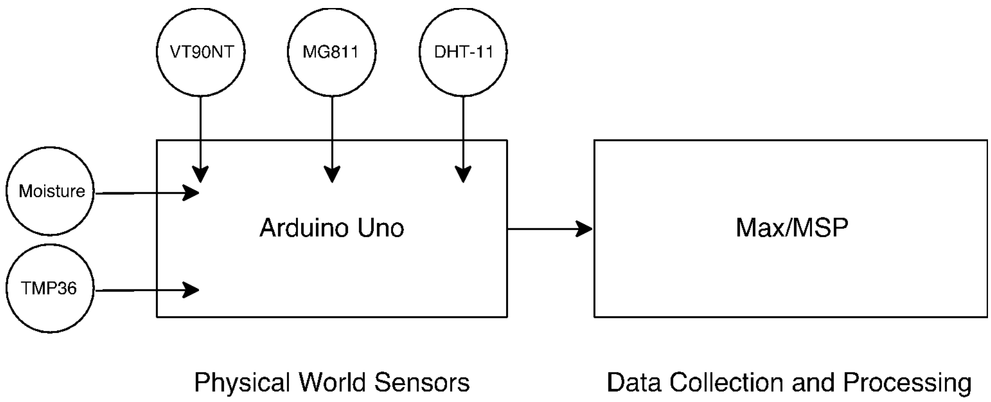

Figure 1. - The data flow of the hardware and software connections

The sensors are connected via copper jumper wires and the Arduino Uno board communicates with the computer via a USB 2.0 digital cable. The MG811 CO_2 sensor requires 6V of power, which exceeds the 5V obtainable through the USB supply. Additional power was provided to the MG811 through a separate, stabilised, DC power supply (Appendix 2).

3.4 Recording and collating

Having established a working prototype that recorded data via the hardware sensors and Arduino microcontroller, the setup was duplicated so one could be housed inside the Rainforest Biome and one inside the Mediterranean Biome at the Eden Project. Each one was placed at ground level, roughly in the middle of each biome. Snapshots of the data measurements were logged every 30 minutes and were taken during visitor hours so that the installation would replay the data at the relative time. The incoming data was stored via the *multislider* object in Max with 18 sliders to collect values every 30 minutes from 09:00 until 17:30. This could then be played back at specific intervals using the *metro* object as a trigger with a value of 1800000 milliseconds.

Figure 2.1 – Multislider object being used to store data. This table depicts humidity values from the Mediterranean biome

As both biomes are made from ethylene tetrafluoroethylene copolymer (ETFE), the light intensity is very similar and differs only because of changes in cloud cover at the time of each snapshot. The data was recorded on 2nd February 2017, which was a particularly cloudy day but nothing unusual for that time of year. The maximum is 5.6 lux at 14:30 and the minimum is 0.1 at 17:30. The measurement of relative humidity (RH) offered a fairly consistent difference of around 10% with a maximum of 11.6% and a minimum of 9.1%. The air temperature is significantly different, as one might expect from these two contrasting environments, with the Rainforest ranging between 18.9°C and 20.4°C and the Mediterranean between 11.3°C and 13.4°C. When reviewing the level of CO_2, it was difficult to understand why the rainforest would contain much higher levels of CO_2 concentration. There is a significant difference in the number of plants within the rainforest biome containing a greater magnitude of plants and therefore a larger surface area of leaf coverage, leading to an assumption that the stomata would be drawing the CO_2 from the atmosphere in superior magnitudes. After conducting some initial research through conversation with the site team, it was ascertained that there are many more visitors each day in the rainforest biome, exhaling CO_2, and there is a minimal amount of ventilation whereas the Mediterranean biome has more ventilation drawing in air from outside and replacing the CO_2 and fewer visitors. The Rainforest biome reached a maximum of 539 parts per million (ppm) and a minimum of 523 whilst the Mediterranean peaked at 425ppm and bottomed out at 412ppm. The soil moisture showed that the water content within the soil of the rainforest was much higher than the Mediterranean which, in turn, influences the relative humidity contrast between the two biomes.

Date / Time	External Light intensity [lux]	Relative Humidity [%]	Air temp [°C]	CO_2 level [ppm]	Soil Moisture
03/02/2017 09:00	0.3	100	18.9	526	604
03/02/2017 09:30	0.6	100	18.9	529	605
03/02/2017 10:00	1.4	100	19	529	602
03/02/2017 10:30	1.3	100	19.2	527	600
03/02/2017 11:00	0.9	100	19.4	525	601
03/02/2017 11:30	1	99.9	19.6	523	599
03/02/2017 12:00	1.4	99.1	19.8	527	598
03/02/2017 12:30	4.1	99.5	19.9	534	598
03/02/2017 13:00	3	99.5	20.3	534	596
03/02/2017 13:30	1.2	99.7	20.4	533	594
03/02/2017 14:00	2.8	100	20.2	537	593

03/02/2017 14:30	5.7	100	20.3	539	590
03/02/2017 15:00	1.9	100	20	535	588
03/02/2017 15:30	2.8	100	20	534	584
03/02/2017 16:00	4	100	20.5	529	583
03/02/2017 16:30	1.3	99.9	20.2	527	581
03/02/2017 17:00	0.6	99.8	20.1	527	580
03/02/2017 17:30	0.1	99.9	19.8	529	578

Figure 2.2 – Data table from the Rainforest biome

Date / Time	External Light intensity [lux]	Relative Humidity [%]	Air temp [°C]	CO_2 level [ppm]	Soil Moisture
03/02/2017 09:00	0.3	90	11.3	412	563
03/02/2017 09:30	0.7	90	11.4	416	563
03/02/2017 10:00	1.4	90	11.6	415	562
03/02/2017 10:30	1.3	90	11.8	419	561
03/02/2017 11:00	1	90	11.9	419	561
03/02/2017 11:30	1	89.9	12	416	559
03/02/2017 12:00	1.4	90	12.3	416	558
03/02/2017 12:30	4	90	12.6	421	556
03/02/2017 13:00	3	90	13.2	422	552
03/02/2017 13:30	1.3	89.9	13.4	422	551
03/02/2017 14:00	2.9	89.5	13	424	549
03/02/2017 14:30	5.6	89.1	13.1	425	548
03/02/2017 15:00	1.9	88.6	12.8	424	545
03/02/2017 15:30	2.9	88.4	12.7	420	543
03/02/2017 16:00	4	88.4	13.2	419	540
03/02/2017 16:30	1.3	88.4	12.9	418	538
03/02/2017 17:00	0.7	88.5	12.7	416	536
03/02/2017 17:30	0.1	88.5	12.4	415	521

Figure 2.3 – Data table from the Mediterranean biome

Chapter 4 – Methodology for Designing a Mapping Framework

4.1 Introduction

The first and most pivotal question to this research project was whether it is possible to generate a sonification of environmental conditions by designing a methodology to create a meaningful mapping framework. Ensuring that meaning was obtained could be as simple as providing a control sound to establish a base point and then using this within the sonification to enable the audience to hear whether data values increased or decreased. For this project, however, further research into how music provides an emotional trigger lead to the investigation of whether it is possible to take the emotional expression associated with music factors and connect these to either a high rate or low rate of photosynthesis. Using Gabrielsson and Lindstrom (2001) review of musical expression as a base, a survey was created in an attempt to establish connections between these expressions and the rate of photosynthesis. With the initial results, a practical exercise to create the extremities of these musical expressions provided a set of audio examples (Appendix 4) by which the associations of musical factors, against proposed high or low rates of photosynthesis, was verified.

4.2 Associations of Musical Factors and Emotional Expressions with Photosynthesis

To influence the audiences perceived emotional expression of the sonification and assess if there was an instinctive or intuitive feeling from the music heard, a review of expressive musical qualities is critical to the design process. Music has immense power to emotionally move an audience and it is this influence on neurological processes that have been the subject of discussion and research for centuries. Music composers rely on perceived music expression to deliver emotional idioms within the construct of phrases, movements and scores. It is through an understanding of how musical structure can influence an audience that allows composers to discuss performance techniques with musicians to elicit expression and therefore play with the emotional response of the listener. It is important to note that any emotion can be experienced by a listener from a piece of music and this subjective view cannot be deemed wrong with any objective evidence of the contrary. Personal experiences are unique and consequently, the emotional response to music is filtered through the history of that person and their preferences. Therefore, meaning in music is somewhat ambiguous and interpretation is varied from one listener to the next (Mitchell and Macdonald, 2011). It was anticipated that the sonification would connect with visitor's past musical experiences and their relationship with emotional feelings to produce a meaningful sonification; offering easily identifiable relationships between the compositions and the environments. The sonification is trying to convey information that is not directly articulated therefore, in order to assess whether the music has communicated more than just melody, rhythm and timbre, the results of the final survey undertaken by the visitors will help to establish if there was associated meaning the final composition. To find associations between these domains two questions needed answering: which musical factors can be used to trigger specific emotions and which of these emotions do we attach to an environment that offers a higher rate or low rate of photosynthesis for plants? Connecting emotional expressions to an environment would be a simpler association to derive relationships between than musical factors as these expressions are better understood by the public than musical terms like timbre. Alf Gabrielsson and Erik Lindstrom undertook a comprehensive review of studies based on factors affecting emotional expression in music; they published the results in 2001. These studies spanned six decades from 1935 to 1999. Having reviewed this study, the key musical factors that could be manipulated by the composition algorithms were isolated and the musical expression associated with these factors identified (Appendix 3). Using musical intervals as an example, Gabrielsson and Lindstrom found that high-pitched intervals evoked emotional expressions related to three terms: happy, powerful and activity. Of low-pitched intervals, the emotional expressions were: sad and less powerful.

Musical Factor	Level	Emotional Expression
Intervals	High-pitched	Happy
		Powerful
		Activity

	Low-pitched	Sad
		Less powerful

Figure 3.1 – example of musical factors and associated emotional expression

The duplicate expressions were removed revealing a final list of emotions that could be associated with musical changes that were possible within the sonification's construct.

activity	agitation	anger	boredom	delicate	disgust
dreamy	energy	excitement	fear	gaiety	glad
gloom	graceful	happy	intense	joy	less powerful
longing	melancholy	peaceful	pleasantness	potency	powerful
sad	sentimental	serene	softness	solemn	strength
surprise	tenderness	tension	tranquil	triumph	whimsical

Figure 3.2 – Data table derived from Gabrielsson and Lindstrom (2001)

To establish associations between these musical expressions and the two states of photosynthesis a survey was undertaken to find common relationships, informing the audio information design and mapping framework for the sonification. The survey question posed was:

> "Plants need CO_2, water and sunlight to photosynthesise and therefore create food so they can grow. Variations in these conditions affect the rate they can do this. Low levels of CO_2, water and sunlight result in a low rate of photosynthesis, high levels of CO_2, water and sunlight result in a high rate of photosynthesis.
>
> Assign the following expressions to describe either an environment that has the potential for a high rate of photosynthesis, or a low rate of photosynthesis"

24 people were surveyed, and the following expression were most commonly linked with either a high rate of photosynthesis or a low rate of photosynthesis:

High Rate of Photosynthesis		**Low Rate of Photosynthesis**	
energy	gaiety	melancholy	less powerful
activity	strength	tranquil	fear
intense	triumph	peaceful	gloom
powerful	pleasantness	serene	dreamy
potency	glad	boredom	tension

excitement	graceful	sad	longing
joy	surprise	solemn	disgust
happy	agitation	softness	tenderness
		whimsical	anger
		delicate	

Figure 3.3 – results of survey 1: Emotional expressions linked to rates of photosynthesis

Using the musical factor 'intervals' as our example as highlighted in figure 3.1, we can see from the survey results that happy, powerful and activity were associated with a high rate of photosynthesis and therefore high-pitched intervals and sad and powerful were associated with a low rate of photosynthesis and therefore low-pitched intervals. Cross referencing the survey results to the initial table (Appendix 3), a final set of contrasting levels for musical factors were derived for both high and low rates of photosynthesis figure 3.4.

Musical Factors	**Level**	**High rate or Low rate**
Amplitude Envelope	Round	LR
	Sharp	HR
Articulation	Staccato	HR
	Legato	LR
Mode	Major	HR
	Minor	LR
Intervals	High-pitched	HR
	Low-pitched	LR
Loudness	Loud	HR
	Soft	LR
Melodic Pitch Range	Wide	HR
	Narrow	LR
Pitch Level	High	HR
	Low	LR
Pitch Variation	Large	HR
	Small	LR
Tempo	Fast	HR
	Slow	LR
Timbre	Many Harmonics	HR
	Few Harmonics	LR

Figure 3.4 – Levels for musical factors linked to rates of photosynthesis

To verify these findings, a set of musical examples for each factor and level were composed and embedded into another survey to see if the results would support the initial findings. To generate the examples, the synthesis models, designed in Max for the sonification, were used and 28 samples created for both level extremities of the 7 musical factors (Appendix 4). Each factor was surveyed twice, using different sounds. The survey question posed was:

> "This survey will attempt to make connections between the rate at which photosynthesis happens within plants and parameters that are common in computer music composition. The results will establish the mapping framework for the musical sonification of the physical parameters predominant in the process of photosynthesis in plants. Each question is presented in the same way.
>
> If the rate of photosynthesis is high, meaning that the temperature is stable and optimum levels of light, CO2 and H2O are present, which of the two musical examples would you associate with this state of photosynthesis and the maximum amount of light energy being transformed into glucose?"

The results from Survey 2 confirm the initial associations convincingly in every factor apart from the variation in articulation. With these factors removed, the stronger verification is 92% confirmation and the lowest 83%. With articulation, the weighting of responses was in favour of the initial survey's findings but with a low of 58%.

Question 1	A	Ex1a_GongDrum_Control	x	A	21
	B	Ex1b_GongDrum_Quiet_-10dB			3
Question 2	A	Ex8b_Chime_FewHarmonics			4
	B	Ex8a_Chime_ManyHarmonics	x	B	20
Question 3	A	Ex2b_GongDrum_SoftEnv			2
	B	Ex2a_GongDrum_SharpEnv	x	B	22
Question 4	A	Ex7a_Chime_Legato			9
	B	Ex7b_Chime_Staccato	x	B	15
Question 5	A	Ex4a_GongDrum_ManyHarmonics	x	A	22
	B	Ex4b_GongDrum_FewHarmonics			2
Question 6	A	Ex6b_Chime_SoftEnv			2
	B	Ex6a_Chime_SharpEnv	x	B	22
Question 7	A	Ex13a_HarmonicDrone_+12st	x	A	21
	B	Ex13b_DissonantDrone_+12st			3
Question 8	A	Ex3a_GongDrum_Legato			10
	B	Ex3b_GongDrum_Staccato	x	B	14
Question 9	A	Ex5a_Chime_Control	x	A	21
	B	Ex5b_Chime_Quiet_-10dB			3
Question 10	A	Ex14a_DissonantDrone			2
	B	Ex14b_HarmonicDrone	x	B	22
Question 11	A	Ex9a_Bells_SmallVariationPitch			2
	B	Ex9b_Bells_LargeVariationPitch	x	B	22
Question 12	A	Ex10a_Bells_FastRhythm	x	A	22
	B	Ex10b_Bells_SlowRhythm			2
Question 13	A	Ex11a_Chimes_SmallPItchVariation			3
	B	Ex11b_Chimes_LargePItchVariation	x	B	21
Question 14	A	Ex12a_Chimes_SlowRhythm			3
	B	Ex12b_Chimes_FastRhythm	x	B	21

Figure 3.5 – results of survey 2: Musical examples linked to high or low rates of photosynthesis

To summarise the two surveys and therefore assign levels of musical factors to either rate of photosynthesis, the final outcome is detailed in figure 3.6.

Level of musical factors for a high rate	Level of musical factors for a low rate
Loud	Soft
High pitch	Low pitch
Large pitch variation	Small pitch variation
Fast tempo	Slow tempo
Many harmonic	Few harmonics
Major harmony	Minor harmony

Figure 3.6 – results of surveys: the level of musical factor against either a high rate or low rate of photsynthesis

4.3 Audio Information Design and Mapping Framework

In designing a mapping framework that offers meaningful relationships between the data and the final audio presentation, the dimensions used to inform the listener of data changes need careful consideration. It is important to understand the level of data comprehension that is required from the sonification. Careful construction of the audio information design principles for the sonification require the artist to understand which streams of data might take precedence within the mapping system; using easily recognizable adjustments of musical factors will help the listener understand relationships between data and music. One of the key goals for *The Photosynthesiser* is that the audience finds some connection within the sonification, resulting in discussion and debate and consequently leading to a deeper understanding of the environment and its role in the process of photosynthesis. The musical qualities that underpin the sonification are subject to the ambiguous interpretation of personal experience, as previously discussed, so choosing the sound source and the manipulation of this requires extensive testing to confirm that emotional impact is within the remit of the artist's aspiration. In analysing the recorded data, decisions on whether *any* alteration of a value, no matter how insignificant, should be audible or if a more holistic approach may be needed where the summation of data is more important. In some instances, it may be required that one data column is followed by another in series rather than a parallel process of sets together, to expose every detail clearly. In order to find some comprehension of meaning within the sonification, the time in which this will take must be considered. Perhaps a short burst of sound is enough for relationships to be found within the data, specifically if the listener has been primed with a control tone or amplitude, or alternatively, the mapping framework used may require prolonged listening before these associations and correlations can be defined. Marty Quinn is a sonification researcher specialising in transforming scientific data into music. His work with NASA "looks to improve the accessibility of data and imagery for the visually impaired" (Bianchi and Manzo, 2016). Quinn (2016) suggests that there are 11 design dimensions that must be considered before the sonification mapping can be implemented:

1. Concurrency vs. Sequential
2. Discrimination vs. Integration
3. Tempo
4. Audio Form
5. Delivery Mechanism
6. Change vs. Stasis
7. Dynamics
8. Instrument selection
9. Audio mix
10. Scale selection
11. Rhythm selection

Using Quinn's dimensions, the audio information design for the sonification can provide a framework in which the mapping can be implemented. As the sonification for *The Photosynthesiser* is based on data measurements that all contribute to the rate of photosynthesis in plants, the combined existence of these elements are the building blocks of the environment and if one key element is removed then the process does not function. Communication of that environment as a whole is therefore fundamental to the sonification and the data streams must coexist within the same space and time for a cohesive impression of the location to be observed. Concurrency of the data is most useful in this case and all streams will be combined within the temporal propagation of the sonification. To decipher meaning from the data, discrimination of exact streams can provide some insight into movements within the data. Individual sensors will be assigned to musical parameters to enable direct perception of data streams within the music but for this system, the use of additional creative input within the compositional model will make this harder to detect. Within the design of *The Photosynthesiser's* information system, there will be a comparison between the summation of data streams to add an additional strand of communication. The environment that offers the conditions for the highest potential rate of photosynthesis will trigger a major chord of frequencies while the other will trigger a minor chord. This is also an aesthetic decision to add an additional layer of musicality to the composition. Quinn (2016) also specifies that within his own sonifications, the necessity to provide interest within the performance is essential, specifically as the sonification may need to be listened to for long periods of time. This observation is also supported within *The Photosynthesiser* and the transformation of data through pure audification may well offer some direct correlation between data and noise or frequency but it is often at the expense of musicality. As tempo has been identified as being an important musical factor within the research, this parameter will be directly related to the humidity, therefore, the intensity of the rhythms and increased tempo will be defined by the data for this condition within each biome. In considering the audio form and delivery mechanism of the sonification, the solution for this project is to record the sonification output and allow for playback via an installation within the environment that the data was recorded. To encourage discussion about the parameters that were measured, the design of the interface and delivery method are crucial and outlined in chapter 5. The nature of the installation and the locality in which it will be housed dictate that a constantly changing sonification will attract attention in those curious enough to investigate whereas a static sonification may well not engage visitors as effectively. This necessity to evolve as a musical composition has been a pivotal part of the design from the inception and the work on generative methods have enabled this system to deliver change. Dynamically, the mapping framework will connect data with amplitude meaning that fluctuations in conditions will create dynamic variation in addition to the algorithms used for sound design providing variations in velocity. This could be hard to distinguish within the final output and the balance between being musically appealing and delivering accurate information may well be compromised. The choice of instrument selection has been identified in chapter 2 and will be constructed on modelling real-world instruments in an attempt to maintain a sense of organic relationship within the sonification for both melodic and rhythmic elements. Apart from the chord generation, all other scale quantisation has been removed from the system and microtonality employed as a way to disconnected with traditional melodic composition. Combined with a patternless output, disregarding the usual compositional techniques such as the use of ostinato or motif's will allow for the analysis of data free of previous associations to learned musical phrases. Quinn's (2016) text outlining the 11 dimensions offered an appropriate foundation on which the sonification design was constructed.

The final mapping framework for the sonification, using the five musical factors selected, was defined as shown in figure 3.7. Using the results of the final survey, the lowest data values were assigned against a low musical factor and the opposite applied for the high values. Light and CO_2 were assigned to amplitude, the temperature to pitch, soil moisture to harmonic content, humidity to rhythm intensity, which would dictate a faster or slower tempo and finally, the sum of all data from each biome compared and the lowest assigned to a minor chord and the highest to a major chord. The audio targets were chosen by allowing the composer some creative input.

Data source	Musical Factor	Audio Target	Low Point	Musical Low	High Point	Musical High
Light	Amplitude	Output level	0.1	-6dBFS	5.7	0dBFS
Temperature	Pitch	Bells & Chime	11.3	C1	20.5	C6
CO_2	Amplitude	Drone	412	-96dBFS	539	-12dBFS
Soil Moisture	Harmonics	All	<570	1000 Hz	>570	18000 Hz
Humidity	Rhythm Intensity	Bell, Chime, Gong and Metallic Hit	88.4	0.4 Probability	100	0.8 Probability
Sum of all	Major / Minor	Pad	Low	Minor	High	Major

Figure 3.7 – The final mapping framework for the sonification – musical factors against recorded data

The table in figure 3.7 is based on the display model created by Dr Davide Tagliapetra (Quinn, 2016) in figure 3.8 that shows the sonification design for the Tides of Venice. This template for displaying the mapping of data to music for sonification is easily understood and provides additional information in much the same way as a key communicates data units within a graphical display.

TABLE 12.2 *The Tides of Venice* Sonification Design

Climate Data Type	Instrument	Musical Expression	Low to high data values map to:
wind direction	flute	pitch. (3 octaves)	low to high pitch
wind temperature	french horn	pitch. (3 octaves)	low to high pitch
tidal level	lush string section	pitch. (middle range 2 octaves)	low to high pitch
humidity	String section	pitch. (high range 1 octave)	low to high pitch
humidity	tympani	Pitch and volume (high range 1 octave) When there is high humidity, you should be hearing a drum roll softly in the background	low to high pitch and very soft to mid volume

(continued)

Figure 3.8 – Quinn (2016) Table to show the sonification design for the Tides of Venice created by Dr Davide Tagliapetra

With a mapping framework defined, the composition algorithms constructed in Max could use the data streams to influence their operation, making changes to the generative nature of their output. The system was left to run whilst the output of Max was recorded. This operation was executed twice, once for each biome and the two resultant audio files used for the installation (Appendix 5. i & Appendix 5. ii)

Chapter 5 – The Photosynthesiser Installation

5.1 Introduction

Designing an installation that can facilitate the playback of audio as well as provide information for those participating and then collect data of their reactions rather complex from the outset, requiring multiple stations to facilitate these prerequisites. Through conversations with App designer, Aaron Tredrea, a set of objectives were drawn up and the testing of such a system could begin. The coding of the App was outsourced to Tredrea and links provided to download the App, install on an iPad and connect to an audio playback system that would work within the rather difficult conditions of the Rainforest Biome at The Eden Project. The result of this system design meant that visitors were able to easily engage with the installation and information dissemination, as well as data collection, was all managed within the App. Having let the installation run for two days the results offered an interesting analysis as to the success of the project, the details of which are outlined in the following chapter.

5.2 Interfacing and Data Collection

With a system that is internally complex but requires effortless engagement with the public, the primary goal was to make the set up for the installation as simple as possible for visitors to engage with. When considering the interface design there were a few straightforward objectives for the installation:

(i) Provide brief but clear information regarding the purpose of the installation,

(ii) allow users to switch between the two compositions seamlessly,

(iii) be able to record user's answers,

(iv) reset after voting to the home screen and opening statement,

(v) store all data until such time that it can be downloaded from the device onto a server,

(vi) work autonomously without the need for intervention or maintenance once set up.

After considering hardware options, the use of a specifically designed application for an iPad provided the right format to offer a physical interface. It permitted for control over the design and function of the software interface and the physical hardware of the iPad touch screen is commonplace and wouldn’t require any guidance on how to control it. An application would also allow for the flow of information to be controlled and the user experience defined. With the support of app designer, Aaron Tredrea, the information and screen flow was detailed and then explored through some initial tests. The first manifestation of the app needed a few small alterations to deliver improvements on the user experience and simplify the information presented. For the prototype, switching between compositions was instantaneous and sometimes, when making the switch, it could be difficult to hear a clear difference to the untrained ear and could cause some confusion. Because of this, the decision was made to incorporate a short fade out and then fade in so there was a defined stop and start between composition options 1 and 2. The second change was to remove a lot of the information provided on the initial home screen. The intention was to minimise any precomposed thoughts regarding the mapping of data to musical parameters and just consider the relationship between each environment and the compositions.

Initially, when designing the installation, it was considered that the system would operate independently of any additional human resource allocation but to find out additional information regarding what had influenced their vote it was decided that a portable record (Zoom H4) would be a useful addition to capture responses when questioned about their choices. It would have been possible to provide a feedback page on the iPad after the vote but the concern here would be a lack of engagement and detail in the responses and if this wasn’t completed the next visitor might find this page confusing rather than being presented with the home screen. A timer could have been introduced to make the app jump to the home screen after a designated time duration but this would hard to quantify, resulting in the screen jumping too early or not early enough. The Zoom H4 was considered to be the most effective audio recording option and was activated as visitors were approach in order to capture reactions. Not everyone who voted wanted to offer a response and they were certainly not pushed to do so as it was not the intention to make them feel uncomfortable. To capture some photo and video evidence a Cannon EOS 550D was positioned close to the installation and activated intermittently. The results of reaction capture were not ideal and there were opportunities missed due to conversations with some visitors whilst other were engaged with the installation and the opening to inquire about their vote missed. The interactions were rather haphazard as engaging in conversation was not easily achieved due to nervous attitudes and social awkwardness from visitors. Frustratingly, when reviewing the audio and looking to analyse and conclude strengths and weaknesses of the project, the interviews didn't follow a set of pre-determined questions and as such provided random results some of which were useful in providing insight into voting decisions, others not so. In review, it is clear that this part of the data collection was an afterthought and not planned effectively.

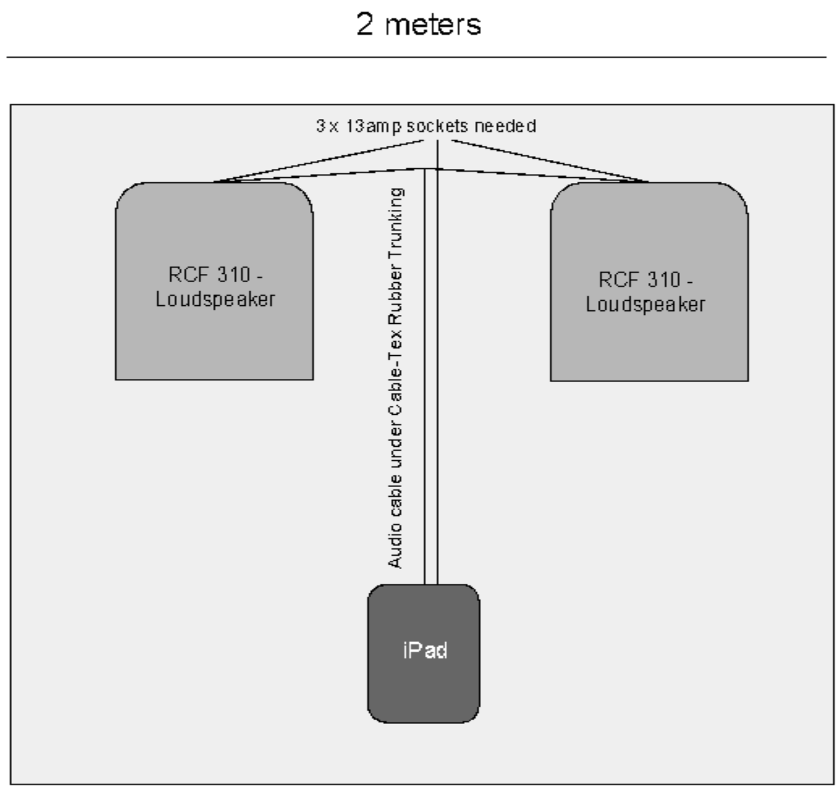

Figure 4.1 – System set up for The Photosynthesiser installation at The Eden Project 24-25th June 2017

5.3 Reactions and Results

To maximise the number of interactions with the installation, it was negotiated with the staff at The Eden Project that a weekend would be most productive, and the installation could run over two days, the 24th and 25th of June 2017. A position for the installation was allocated within the rainforest biome after some initial sound levels readings were taken and the power requirements provided to the Edan team prior to my arrival. The area was selected due to the spacious nature and low sound level interference or 57.9 dB SPL (Appendix 6), in comparison to the other potential position of 63.7 dB SPL (Appendix 6), close to the rainforest research information point. The three main concerns were the impact of the humidity and moisture of the environment on the hardware, when left for a long duration and the presence of white-footed ants which, according to Michael Cutler the horticultural technical engineer at Eden, 'are extremely efficient at eating through cables'. To minimise the potential of either of these issues the installation was run from 10:00 to 16:00 on both days, then packed up and stored on site outside of the biome. Over the two days 121 visitors listened and voted for the composition they believed was generated from the environment inside the rainforest biome. Of the 121, 12 voted for composition number 1 and 109 voted for composition number 2. Composition 2 was the correct choice and was composed of data recorded inside the rainforest biome meaning that:

90% of visitors correctly identified the environment from the music.

This was a much greater than had initially been anticipated and if the result had been over 50% it could have been possible to say that the mapping framework was, to some extent, successful and the quantitative research that influenced the design was justifiable. At 90% the result is much more conclusive, the methodology validated and the proposed connections between musical factors and rates of photosynthesis reinforced. Through visitor comments such as audio interview evidence 1 and 4 (Appendix 7) it is possible to hear primary evidence to support this.

> "Because it was more dramatic, there was more going on, so you imagine that in the rainforest one the sensors pick up a lot more, more heat, more temperature. The idea that there would be far more fluctuations, far more highs and lows in the factors like CO_2, light, humidity." (Appendix 7. i)
>
> "Because of the intensity of the sounds. The higher pitches as well" (Appendix 7. ii)

It is certainly obvious from these comments that what was potentially a rather ambiguous connection between musical factors and rates of photosynthesis held firm, as without informing the audience of the mapping framework they were commenting of the precise detail of the process from purely listening to the two compositions side-by-side. The results were exceptionally poignant in confirming that there was a perceived relationship between the two compositions and the biomes and thus a meaningful message in the designed mapping framework. The reaction of the visitors in the audio interview evidence (Appendix 7) further illustrates the strength of the framework and proves that the musical factors associated with the rate of photosynthesis held firm with the public's perception of this rather abstract concept. This evidence demonstrates there was a clear delivery of information that was not directly expressed through written or verbal communication. The iPad app created for the project provided a perfectly simplistic system for audio playback and data collection without intruding on the installation.

Chapter 6 – Conclusion

6.1 Knowledge Gained from Questions Posed

Throughout this project, the trajectory and outcomes have been somewhat malleable as ongoing research resulted in new knowledge and this, in turn, affected what was and was not possible in regard to the concept of *The Photosynthesiser*. Discovering how Barnard et al. (2014) used Arduino to create a cost-effective system for recording environmental fluctuations was a key moment in this project's development and allowed for greater autonomy in the development of the system by enabling the construction of the physical sensors and freedom to record and test prototypes. Works by Schafer, R. (1997), Hermann et al, (2011) and Polli, (2016) provided inspiration in contextualising the worth of musically tracking our surroundings in conjunction with the importance of sonification as a scientific method - as well as a form of sound art. Wrestling with questions of validity for such a piece of work was at times tough, as the initial hope of making changes to human behaviour was ambitious but is still possible with future developments offering more emphasis on disseminating information through interactivity and a concise framework for questions and discussions. There has, however, been a core set of questions - posed in the introduction - that has driven the project forwards, influencing the direction of the research and accumulating new knowledge:

- Is it possible to generate a sonification of environmental conditions by designing a methodology to create a meaningful mapping framework?
- What musical factors can be used to trigger specific emotions and which of these emotions do we attach to an environment that supports a higher or lower rate of photosynthesis in plants?
- Can the sonification have meaning and therefore communicate information through the association to environmental conditions yet still offer generative possibilities and forever evolve - even with the same data set?
- What is the overall value of this research and how can it be further developed?

As a sonification that offers meaning, in such a way that two contrasting environments could be differentiated by the music they created, *The Photosynthesiser* has proven to stand up to the initial challenge with a 90% success rate. By constructing a mapping framework that was based on musical factors related to emotional responses, intuitive associations were made and ultimately, these instinctive reactions were accurate nine times out of ten. Through exploration of the categories of sonification the choice of PMSon was an obvious one, allowing for continuous data representation as well as the incorporation of artistic license by the system designer. The composition design and mapping framework have proved appropriate and convincing in conveying climatic information when the sonifications are played side-by-side. As the visitors were familiar with the contrasting conditions between the two biomes, relating this to two musical compositions and being able to compare them instantaneously, makes extracting meaning from the music infinitely easier through this association. Using this framework to portray the conditions of one environment in an attempt to gain meaningful information would ultimately be unsuccessful given that there is no control to compare to. In this scenario, the *keynote* proposed by Schaeffer for his soundscapes becomes an integral factor; to know if one of the conditions is increasing or decreasing a control tone must be established.

The methodology used to define the musical factors that were manipulated by the data was justified in the final outcome, however, with only 24 people surveyed it is far from comprehensive. Large leaps in imagination were needed to relate musical factors to the rate of photosynthesis but it provided a starting point to begin developing a framework for the mapping process. Reviewing the discussions that happened as visitors were voting and then reflecting on their choices offered additional support to the mapping framework, such as *Audio Example 4* (Appendix 4. iv), where the intensity and higher pitchers were key triggers in making the connection between environment and musical composition. As a result of the surveys, decisions such as increasing rhythm intensity with higher levels of humidity were defined - and again justified in the reactions of the visitors - as with *Audio Example 1* (Appendix 4. i) and *Audio Example 2* (Appendix 4. Ii).

The hours of practice-led research spent manipulating compositional algorithms to enable a stochastic and generative system produced encouraging results. The subtle variations in harmonic relationships, pitch, rhythm and amplitude of the system contain sufficient randomness at the output to minimise any exact repetition and continued triggering through the impulse generation, maintaining endless signal generation. With the exact same data streams incessantly sent to the system, these musical parameters would still continue to evolve ever so slightly through the implementation of the *random* object in Max and therefore it is near impossible to detect a repetitive phrase or motif within the rhythmic or melodic output. With this object, the range of randomness was controllable, so the extent of change was defined within the system. With a change to the dataset, the magnitude of this deviation can be targeted and the system then reacts to the variations creating a relationship between data and sound, delivering on the goal of a parameter mapped sonification.

The value of such research can be somewhat subjective depending on individual interests but, from the outset, the intention was that in listening and understanding a little about the installation and the concept behind it, discussions on the environment and climate would ensue. This engagement with important scientific questions from a simple musical composition is where the integration of art into our well-established STEM programme appears to have a valid place. The installation made visitor really consider the difference between each biome in relation to those conditions vital to photosynthesis in plants. Instead of just admiring the flora and fauna visitors began to consider what the elements were that enabled these magnificent plants to thrive, especially those only just learning about the photosynthesis process and how this is ultimately responsible for all life on earth. It helped parents gauge their children's understanding of this biological phenomenon to help them grow in their understanding. Watching this take place provided moments of great delight and reward and gave further confirmation of how art can support changes in human behaviour. The lack of a measured framework for the questioning of visitors into what additional meaning they gained from the installation was detrimental to the project and should certainly be revisited for future installations. The process was rather ad-hoc and started with 'why did you choose composition 2 (or 1)'. Although some visitors were sufficiently cognitive and eloquent with their answers to gain insight into their thought process, a set of additional questions would certainly have helped in developing a more comprehensive analysis of the success of the project and whether it supported further discussion on environmental issues. There were occasional moments where this was evident, especially when discussing the levels of CO_2 within each biome as this was in opposition to what one might suppose and here the conversation led on to global CO_2 levels and the threat that this trend poses to the rising temperature of our planet.

As Ground and Berger (2011) suggested, there is usually a compromise within a PMSon system against the three categories of intuitive, pleasant and precise. From the final results, it is perhaps safe to say that the mapping framework was intuitive for most people as they made the correct analysis of the sonification. Comments on the enjoyment of the music helped to verify whether, somewhat subjectively, the sonification was pleasant and allowed scope for prolonged listening. The fact that two visitors asked where they could buy the music for recreational listening helped reinforce this view - however, this is difficult to attest to everyone's perception and those who found it ultimately unpleasant might well have not wanted to declare this for fear of offending.

6.2 Future Developments

This research project may provide further insight into small fluctuations in climatic factors if experienced over a long period of time to the point at which subtle deviations in sonic character are audible: relatable to changes in the environment. The mapping framework can be adjusted with threshold points established within the system to provide extreme alterations in the musical output once a particular condition is met. This could prove useful in the world of agriculture, specifically for those with visual impairment who cannot look at displays to perceive conditions of crops or the manipulated environments the plants grow in.

Interactivity, as a means to engage the public, is another avenue that has plenty of scope to be explored. Even within the planning phase of this project there had been the desire to use a set of MIDI control faders assigned to override the data streams for Temperature, Soil Moisture, Light and CO_2 so that it would be possible to develop it as a musical model to understand what might happen when the CO_2 concentration levels of the earth surpasses 450ppm, for example. In this system, once CO_2 or temperature exceeded a set threshold, it would be possible to make the sonification become rather unpleasant to listen to, with deterioration of signals through distortion or the integration of more and more white noise to indicate the potential collapse of Earth’s atmosphere. This provocation of difficult listening conditions would reinforce the difficulties the human race faces if we do not revise our actions and look to change our behaviour for the future protection of our planet. These specific scientific messages could be delivered in conjunction with the installation and support the ongoing use of art to nurture our ability to explore concepts from multiple angles as suggested by Land (2013). Rather as Polli (2016) wanted people to physically experience, through sound, future change based on prediction models of temperature rises, *The Photosynthesiser* can offer similar experiences with increasing distortion and white nose becoming unbearable in the way in which our own environment certainly will if we do not heed current research. Comments from staff at The Eden Project (Appendix 8) also highlight the worth of this project in an educational setting and, as it is a portable system, the sensors can be positioned anywhere and data recorded for the use of scientific analysis through sonification or enjoyed purely as a piece of sound art.

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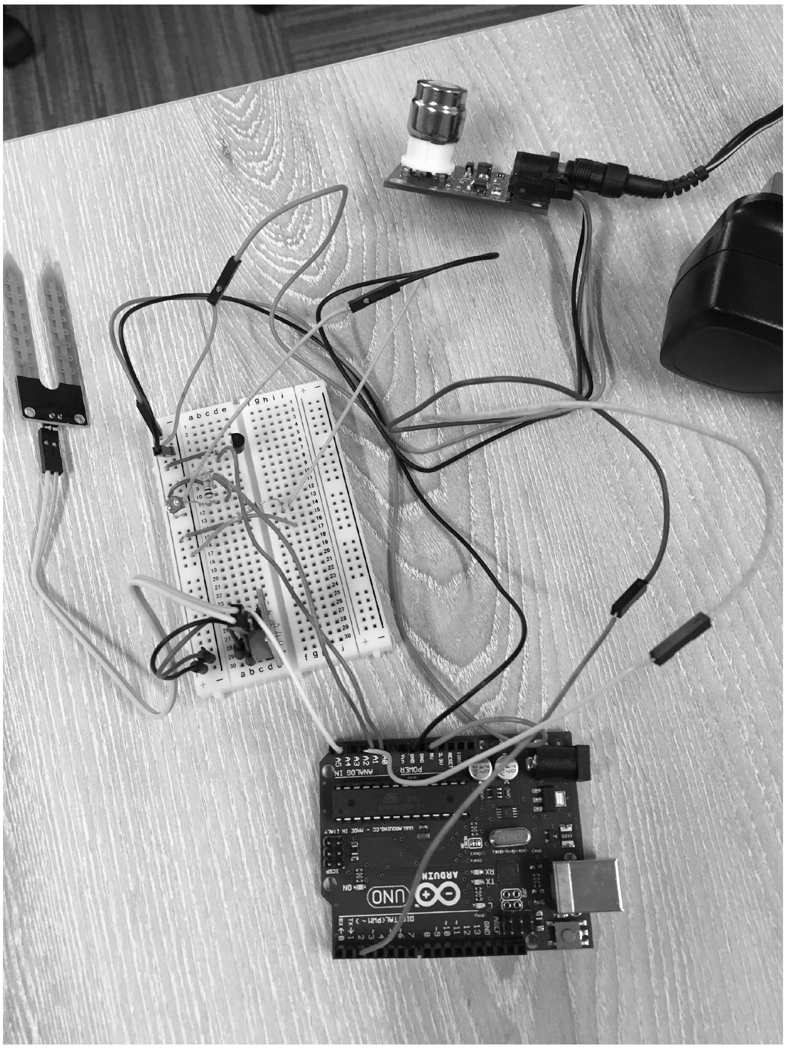
Appendices

Appendix 1 – Sounds from Max

i. Gong.aif - https://drive.google.com/open?id=1Hsk9tS9Kuk-jVrbVnVsOlq9tzTD4sRhl
ii. Metallic Hit.aif - https://drive.google.com/open?id=1IMQqYCEfvb6xUP3rFmfgzic2IfGiCLxK
iii. Bells.aif - https://drive.google.com/open?id=1IP8JFahAMqBFGIUb5wRDlsh1Y8itPn5D
iv. Chimes.aif - https://drive.google.com/open?id=1IPaWdmYt99SfA0h9i3wzs5drRmDLp-wS
v. Harmonic Drone - https://drive.google.com/open?id=1Hm_Z37GlnpnahVUF6sDuffKWVmV6FL9m
vi. Harmonic Drone +12 - https://drive.google.com/open?id=1HfrfA5MxbBmAl7BKRJoIuoBdKpyRBWxP
vii. Dissonant Drone - https://drive.google.com/open?id=1Hp09n_xhXQIEUVCPMwveh1ngvXssgt97
viii. Dissonant Drone +12 - https://drive.google.com/open?id=1HlvzX_5jrSEVaTayoqnYUYQ_nrLE7ckh

Appendix 2 – Arduino Microcontroller and Physical Sensors VT90N2 LDR, VT900 Series, TMP36, MG811, DHT-11.



Appendix 3 – Survey of musical factors that affect emotion

Factor	Levels	Emotional expression
Amplitude Envelope	Round	disgust
		sadness
		fear
		boredom
		potency
		tenderness
	Sharp	pleasantness
		happiness
		surprise
		activity
Articulation	Staccato	gaiety
		agitation
		intensity
		energy
		activity
		anger
	Legato	solemn
		melancholy
		softness
		tenderness
		sadness
Mode	Major	happy
		joy
		serene
		strong
		activity
	Minor	melancholy
		sad
		gloom
		tension
		agitation
Intervals	High-pitched	happy
		powerful
		activity
	Low-pitched	sad
		less powerful
Loudness	Loud	excitement
		triumphant
		intensity
		strength

		power
		tension
	Soft	melancholy
		delicate
		peaceful
		softness
		tenderness
Melodic Pitch Range	Wide	whimsical
		glad
		uneasy
		joy
	Narrow	melancholy
		sentimental
		tranquil
		delicate
		sadness
Pitch Level	High	graceful
		serene
		happy
		joy
		dreamy
		triumph
		exciting
		activity
	Low	sad
		melancholy
		solemn
		tranquil
		boredom
Pitch Variation	Large	happiness
		pleasantness
		activity
		surprise
	Small	disgust
		anger
		fear
		boredom
Tempo	Fast	exciting
		uneasy
		triumph
		happy
		glad
		gaiety
		joy
		graceful
		activity
	Slow	serene

		tranquil
		dreamy
		longing
		sentimental
		sad
		solemn
Timbre	Many Harmonics	potency
		anger
		fear
		activity
		surprise
	Few Harmonics	pleasantness
		boredom
		sadness

Appendix 4 – Samples of Musical Factors used in Survey 2

The following sounds can be access via the following link:
https://drive.google.com/open?id=1EKj7XUHtOiH9V_VGLM_Z2v-xybuX0pxz

- Ex1a_GongDrum_Control.mp3
- Ex1b_GongDrum_Quiet_-10dB.mp3
- Ex2a_GongDrum_SharpEnv.mp3
- Ex2b_GongDrum_SoftEnv.mp3
- Ex3a_GongDrum_Legato.mp3
- Ex3b_GongDrum_Staccato.mp3
- Ex4a_GongDrum_ManyHarmonics.mp3
- Ex4b_GongDrum_FewHarmonics.mp3
- Ex5a_Chime_Control.mp3
- Ex5b_Chime_Quiet_-10dB.mp3
- Ex6a_Chime_SharpEnv.mp3
- Ex6b_Chime_SoftEnv.mp3
- Ex7a_Chime_Legato.mp3
- Ex7b_Chime_Staccato.mp3
- Ex8a_Chime_ManyHarmonics.mp3
- Ex8b_Chime_FewHarmonics.mp3
- Ex9a_Bells_SmallVariationPitch.mp3
- Ex9b_Bells_LargeVariationPitch.mp3
- Ex10a_Bells_FastRhythm.mp3
- Ex10b_Bells_SlowRhythm.mp3
- Ex11a_Chimes_SmallPItchVariation.mp3
- Ex11b_Chimes_LargePItchVariation.mp3
- Ex12a_Chimes_SlowRhythm.mp3
- Ex12b_Chimes_FastRhythm.mp3
- Ex13a_HarmonicDrone_+12st.mp3
- Ex13b_DissonantDrone_+12st.mp3
- Ex14a_DissonantDrone.mp3
- Ex14b_HarmonicDrone.mp3

Appendix 5 – Extracts of the Sonification for the Mediterranean and Rainforest Biomes

i. Mediterranean Biome: https://drive.google.com/open?id=1IwwdhbmB7IyIumyIHanL-Vy7rvxDS8Be

ii. Rainforest Biome: https://drive.google.com/open?id=1J-pZBzSRd1Onj49NhkQTxg8z1Vify1fy

Appendix 6 – Background Noise Within the Rainforest Biome at The Eden Project

Appendix 7 – Quotes From Visitors After Having Voted For Their Choice

A selection of interviews can be accessed via the following link:
https://drive.google.com/open?id=1EJbzeAEIJNBhqEt9sJh2fEzQNIO0IWr8

Why did you think number 2 (or 1)?

- Audio Interview Example 1

"Because it was more dramatic, there was more going on, so you imagine that in the rainforest one the sensors pick up a lot more, more heat, more temperature."
"The idea that there would be far more fluctuations, far more highs and lows in the factors like CO_2, light, humidity."
It's made its own sound that sounds that actually sounds a bit like a rainforest.

- Audio Interview Example 2

I think the 2nd one is the rainforest as it's more changing and less consistent.
I would say that's right and it is kind of faster

- Audio Interview Example 3

"There is more happening in this one and there is more happening in here, the rainforest"

"It just feels more like the natural sounds of a rainforest"

- Audio Interview Example 4

"Because of the intensity of the sounds. The higher pitches as well"

- Audio Interview Example 5

"This one, which in comparison is nice and calm. It's got the kind of chimes that I picture with a Mediterranean atmosphere but when I played this one (composition number 2) it all of a sudden became very intense."

Appendix 8 – Quotes from Staff at The Eden Project

- "After having a lengthy conversation with the lovely Oli, I thought it was fantastic as you get to close your eyes and imagine the tempos. I think this would be great as another form of sensory communication instead of having the sounds of the Rainforest and Mediterranean, with birds and waterfalls going but whole new sounds. I did guess the correct sound automatically as I just imagined the sound of raindrops as they hit the ground that you don't tend to hear. So it's going past the every day noise that we are used too and really puts in a whole different experience. I enjoyed the Mediterranean sounds as it was very quiet and then suddenly noise, which is exactly like the Mediterranean, (especially when a school group just comes in). I would love to see this come back again! It reminds me off the wind, fire and water study that came in, almost three years ago in the Core. That was amazing, to watch fire dance to music. I know we can programme music to lights as I done this with my music degree, but watching fire dance, AMAZING!"

- "The audio installation was for me very interesting. It was good to think about the Rainforest Biome differently. Although knowing about all the things Oli was measuring it was fun to hear it and be able to think of it. Day to day you don't really think about the CO2 levels and the things Oli was measuring but it was a nice way to get back in touch with all that. Knowing what I know about the Rainforest it became a little obvious which was the sound of the rainforest, this only became more obvious when he started to explain what he had measured to make the sounds. It would be interesting to see how other people came to their conclusion, especially as 90% were right."

- "I stopped by and thought it was very interesting to hear such a difference. I did mention at the time that it would have been interesting to hear a recording of outside also but I understand that there were time constraints. It would have also been interesting to hear how they compared to other areas, inside a house for example to give a real idea of the difference between these areas. I also thought that whilst it was interesting there wasn't enough information about why this work will be beneficial and who to. I did ask and understood but it could be made more obvious to the general public."

- "I thought the idea of the Biomes making their own music is amazing, and hearing the audio was both creepy and beautiful with the tones on both recordings. Oli was very welcoming with a huge smile and just by talking to him I could tell he was very passionate about his work."

A collection of photos and videos of the installation can also be access via the following link:
https://drive.google.com/open?id=0B6knoA3iQPzaTDlaMUJ4T1EtVDg