Aural evolutions: intersections of sound with the physical space
Efthymios Chatzigiannis (2011)

NB Three accompanying CDs and one DVD

Note if anything has been removed from thesis:

Aural Evolutions

Intersections of Sound with the Physical Space

PhD Thesis by
Efthymios Chatzigiannis
Student No. 07101923

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Abstract

This is a practice-based research project situated at an intersection between the fields of electroacoustic composition, experimental composition, and sound art. The general research context for this project is a territory that engages with sound as a physical medium, and is concerned with the representation of acoustic phenomena through sound art and experimental composition. Practitioners in this territory include Alvin Lucier, Sato Minoru and Carsten Nicolai. The present study extends this territory in order to focus on the representation of mechanisms that affect the evolution of a sound from the moment it is produced and until it reaches our perception. Each work presented in this thesis deals with the representation of specific elements of an acoustic phenomenon that are capable of shaping the form of a sound. In doing so, this research project contributes with an original portfolio of works that explore the representation of elements such as the relationship of the size of a space with the frequency of a sound that is produced inside this space. As a result from this process, this study exposes intersections and analogies between the material and the energetic space as they are manifested by the evolution of sound as a physical phenomenon, and engages the audience in experiencing the meeting points of these two spaces.

Table of Contents

Introductory statement

This research project explores the space between a sound source and the listener to that sound source, at the moment that sound is produced. As soon as this sound is produced it begins a journey towards the listener, and during this journey it is transformed through various interactions with the environment that the sound source is located within. Through an exploration of the transformations that occur during this journey, the connections between sound and the physical environment within which is located become evident. Through the platform of composition and sonic art, this study reveals these connections to an audience while focusing on elements that interact with the sound during its journey from the sound source to the listener. Specifically, the aims and questions of this research project are[1]:

- To explore the way in which sound changes and evolves between the sound source and the listener.
  - How do we perceive the evolutionary process of a sound, from the moment it is produced and until it enters our perception?

- To expose the intersections and analogies between the material and the energetic space through the exploration of the physical evolution of a sound.
  - How can we categorize and explore the intersection of sound with physical space?

[1] The aims and questions will be discussed in depth in the next section

- To explore the aforementioned areas through the practice of composition and sonic art.
  - How can we employ these observations in the compositional process as means of using the physical behaviour of sound in order to manipulate an acoustic signal?
  - Which compositional practice, or practices, can provide a context for the exploration of the intersection of the physical and the energetic space through the medium of sound?

In order to address these questions and explore the evolution of an acoustic signal in the environment within which it is located, this study focuses on the changes that occur in this environment and the way these changes can shape the form of the sound that is being audited. The general methodological approach of this research project has been the audition of the relationship of a sonic event with the specific conditions of the environment within which it is located. The first method has been the audition of the same sonic event in different environmental conditions: the same sound was audited moving through different mediums for example, or echoing in spaces of different sizes[2].

The second method aimed at the understanding of the acoustic phenomenon that caused the changes in the form of the sound being perceived, revealing the link between the evolution of the sound and the environment within which this sound is located. This method included some

[2] A detailed description of the sonic observations is included in the 'Methodology' section, in the chapters relating to each work. Documentation of these observations can be heard on Audio CD 3 – Field Recordings.

theoretical research on the acoustic phenomenon in question, as well as on the work of other artists that have explored similar phenomena. The main focus however has been on practical experimentations with the acoustic phenomenon in question and the creation of mechanisms that manipulated aspects of the physical space that related to the acoustic phenomenon in question: mechanisms that were changing the size of the space in which a sound was being transmitted for example.

1. Aims and Research Context

*'But when you listen to music do you ever stop to realize
that you are being subjected to a physical phenomenon?
Not until the air between the listener's ear and the instrument
has been disturbed does music occur.'*

Edgard Varése[3]

1.1 Aims and questions

This is a practice-based research project located in a territory between the fields of experimental composition, electroacoustic composition, and sound art. The project activates creative processes, methodologies, and modes of representation from these fields in order to create works that represent the evolution of sound in physical space, between a sound source and our perception of the sound this source produces. Through the exploration of this evolution, the works detailed in this study reveal intersections and analogies between sound and the physical space, and contribute to our understanding of the relationship between sound and physical space by creating experiences that engage the audience in an exploration of this relationship. More specifically, this research project has three general aims:

<u>Aim 1:</u>

- To explore the way in which sound changes and evolves between the sound source and the listener.

[3] Edgard Varése, *Music as an art science*, lecture given at the University of Southern California in 1939, published in *Contemporary Composers on Contemporary Music*, 1998, edited by Elliot Schwartz and Barney Childs, Da Capo Press Inc., p. 199

‘vibration phenomena of a specific space are shaped not only by the source of the vibration, but also by the state or the conditions of the space through which they are being transmitted’[4].

Sound is a vibration that can evolve differently in different spaces, and its evolution is related to the condition of the space in which this sound is being produced. Alvin Lucier once explained to William Duckworth that his work is ‘dealing with lengths of sound, it’s physical dimensions. Even what happens in *I am sitting in a room* depends on the physical dimensions of the room and what wavelengths fit in it’[5] and Curtis Roads informs us that ‘every sound has a three-dimensional shape and size, which is its diffusion or dispersion pattern over time’[6].

The first aim of this research project is to explore new ways – and to build upon old ways – of manipulating the diffusion of a sound, and changing the shape of this sound physically. Through this practice, the works produced as part of this study explore the evolution of the shape of a sound through its physical behaviour. In order to work towards this aim, one question had to be addressed:

- How do we perceive the evolutionary process of a sound, from the moment it is produced until it enters our perception?

The first step in the exploratory process of the evolution of sound has been to develop a strategy for the audition of this

[4] Toshiya Tsunoda, 1999, *About 2 works*, published in *Site of Sound: of Architecture and the Ear*, Errant Bodies Press – Smart Art Press, p. 146

[5] Alvin Lucier, 1981, *Discovery as part of the experience*, conversation with William Duckworth, published in *Alvin Lucier: Reflections*, 1995, Music Texte, p. 42

[6] Curtis Roads, 2004, *Microsound*, The MIT Press, p. 39

evolution through everyday sonic experiences. This strategy relies on the audition of the same sonic event in different situations, and the documentation of the differences that are heard on the sound in each situation. The situations are then analyzed, focusing on the elements that interact with the sound source and the difference in the states of these elements in each situation.

For example, if we listen to the sound of a clinking glass when the glass is empty and when it contains a liquid that moves inside it, we will notice subtle fluctuations in the frequency and amplitude of the clinking sound when there is a moving liquid inside the glass. This behaviour manifests the relationship of the evolution of the shape of a sound with the movement of the medium in which this sound is transmitted. Some of these observations were recorded and can be heard on Audio CD 3 – Field Recordings. Each one of these observations is related in different ways to each of the works presented in this thesis, and their relationship will be discussed in the relevant chapter detailing each work.

<u>Aim 2:</u>

- To expose the intersections and analogies between the material and the energetic space through the exploration of the physical evolution of sound.

> ‘the […] material space, is defined by the traditional, classical, architectural tectonics: walls, ceilings, floors, windows, etc. […] The second type of space,

> called the energetic space, is defined by sensory qualities, such as warmth, smell, colour, light and sound' [7].

Sound exists in the energetic, immaterial space. Most of the time it is perceived as an aural, and not as a physical, sensation. In several instances however, sound can make its presence noticeable in physical ways. Composer Pauline Oliveros recalls an experience she had with the sound of a car:

> A very low frequency is shaking my belly. (7 Hz at high intensity can make you sick or kill you.) It is an automobile becoming more apparent as it passes, now accented by a motorbike.[8]

Loud, low frequency sounds are very good examples of the intersection of sound with the physical space. Low frequency sound waves are long, and intrude the material space by moving big masses of air that can interfere with physical objects.

The second aim of this research project is to explore these analogies between the physical and the energetic space, through the evolution of a sound in the space between its source and our ears. Several of these analogies are evident in the relationship of sound with the physical space in which this sound is being transmitted. Such an exploration will contribute to our understanding of the intersection between these two spaces by engaging the audience in experiencing the commonplaces between physical and sonic dimensions. Working towards this aim, one question was addressed:

[7] Sven Sterken, 2001, *Towards a Space – Time Art: Iannis Xenakis' Polytopes*, article published in Perspectives of New Music, Vol. 39, No. 2 (Summer 2001), pp. 262 – 273.

[8] Pauline Oliveros, *Some Sound Observations*, re-published in *Audio Culture: Readings in Modern Music*, edited by Christoph Cox and Daniel Warner, 2006, The Continuum Publishing Group Ltd, p. 103

- How can we categorise and explore the intersection of sound with the physical space?

The general concept of the intersection of sound with the physical space is divided into two conceptual frameworks: the relationship between sound and the size of the space in which this sound is produced, and the relationship between sound and the medium in which this sound is being transmitted. Each individual work presented in this thesis is defined by one of these two frameworks, and explores a phenomenon that is manifested within one of these frameworks.

In answering this question this project contributes with two conceptual frameworks for the exploration of the phenomenology of sound through the medium of sound art. Analogies between the physical space and sound have been identified and categorized such as the relativity of the size of the space in which a sound is being produced with the frequency of this sound, or the relationship between the movement of the medium through which a sound is being transmitted with the frequency and dynamics of the sound.

<u>Aim 3:</u>

- To explore the aforementioned areas through the practice of composition and sonic art.

The works presented in this thesis respond to the physical evolution of sound, by presenting elements that can shape this evolution from the moment a sound is produced and until it enters our perception. In order to achieve this, each work deals with a specific element that operates during the occurrence of an acoustic phenomenon, such as the movement of the medium through which a sound is being transmitted, or the way in which the size of a space determines the resonant frequency that this space will amplify if a sound is produced inside it.

The element that contributes to the evolutionary process of sound is presented to the audience in the form of an aural, or audio-visual, metaphor. In doing so, this project contributes with a portfolio of new works that focus on the exploration of the mechanisms that instigate acoustic phenomena, and the way in which these phenomena contribute to the evolution of a sound in the physical space and shape our perception of this sound. Working towards this aim, two questions needed to be addressed:

- How can we employ these observations in the compositional process as means of using the physical behaviour of sound in order to manipulate an acoustic signal?

Practice based methods[9] have been applied for the exploration and understanding of acoustic phenomena and their subsequent

[9] These methods will be discussed in detail in the Methodology section of each work.

use as a means of manipulating a sound. These methods begin with the observation of an acoustic phenomenon and the mechanisms that operate for its creation. Practical experimentation with these mechanisms helps the development of an intuitive understanding of each phenomenon in question, and leads to the creation of a work that presents the elements of this phenomenon to an audience. Some examples of the results of these practical experimentations can be heard on Audio CD 2 – Research Recordings. Their relationship to each work will be discussed in the relevant chapters.

- Which compositional practice, or practices, can provide a context for the exploration of the intersection of the physical and energetic space through the medium of sound?

The purpose of this study is to explore strategies that use the phenomenology and physics of sound and manipulate - and/or produce - a sound, in order to represent the intersection of the material and energetic space through the physical evolution of sound. Working towards such a complex aim, different approaches and representational methods were considered. Within the two conceptual frameworks mentioned previously (sound/space and sound/medium), the project moves between different disciplines of music composition and experimental sound making in order to explore different modes of representation for the relationship between the material and energetic space through the medium of sound.

The project looks into works by sound artists and composers that engage with sound practice in different ways, but their work is always concerned with the representation, and/or use of physics, science and technology. Sound artists and composers Alvin Lucier, Sato Minoru, Toshiya Tsunoda, Carsten Nicolai, Christina Kubisch and Jonty Harrison define the general research context of this project, and each of the works presented in this thesis has a unique relationship with each one of these practitioners. Building upon the practices of these artists, this project contributes to the tradition of engaging the phenomenology of sound in the compositional process as a way of producing, organizing, and/or manipulating a sound.

1.2 Research Context

This research project brings together different elements from the fields of electroacoustic composition, experimental composition, and sound art, in order to engage in a territory that responds to the relationship between the material and the energetic space, through the evolution of sound. My working definition of this territory is “evolutionary sonology”: engaging in a practice of experimental sound-making that is concerned with the representation of the evolutionary process of sound in the physical space, and creates works that respond to specific elements that affect this evolution. The works use different means and methods of representation appropriate for the presentation of the evolution of a sound, as this sound is being transmitted through an element that can affect this evolution (i.e. a moving medium, or a space whose size changes).

Key practitioners from the above mentioned fields of sound practice provide the research context for each of the works produced as part of this study. This section is an introduction to the practitioners that provide a context for the creation of each piece produced as part of this research project, and serves as a review of their approach and its relationship to this study. Their contribution to the context of each work will be discussed in detail in the chapters relevant to each work in this study.

- Alvin Lucier (b. 1931)

Alvin Lucier is an experimental composer who produces work that explores the amplification and presentation of acoustic phenomena and is ‘interested in the phenomenology of sound and the revelation of its natural characteristics and processes as music-making’[10]. As Brandon LaBelle suggests, Lucier’s work ‘extends the scope of experimental composition to engage sound as a physical medium’[11]. The engagement with sound as a physical medium through the practice of musical composition is the general context of this research project.

In his approach however, Lucier is more interested in the amplification and presentation of physical phenomena through the use of technology. In works such as *Music for Solo Performer* (1965) and *I am sitting in a room*

[10] Pauline Oliveros, *Poet of Electronic Music*, introduction to *Alvin Lucier: Reflections,* Musik Texte, 1995, p.12

[11] Brandon LaBelle, 2006, *Background Noise: Perspectives in Sound Art*, The Continuum International Publishing Group Ltd., p. 125

(1969) Lucier is interested in amplifying otherwise imperceptible phenomena, and presenting these phenomena to an audience: in the first case through the use of vibrating percussive instruments, and in the second through the sound of his voice interacting with a space.

My work responds to the general approach of sound as a physical medium, and extends this territory by specifically focusing on sound as a physical medium that evolves through its interaction with other physical mediums and/or objects. Rather than amplifying and presenting an acoustic phenomenon, my work magnifies the process of sonic evolution through the application of this process to the transformation of a sound. Two works by Alvin Lucier provide the research context for my pieces *Tonality measured by distance* (refer to the video documentation on the DVD) and *Auditory Rainbows* (Audio CD 1, Tracks 2 and 3):

- *I am sitting in a room* (1969)

  In this piece Lucier explores the ability of the human voice to trigger the natural resonant frequencies of a space. This piece provides the research context for my sound installation *Tonality measured by distance*. My installation extends this principle, and creates a metaphor that demonstrates the relationship between the natural resonant frequencies of a space, and the size of that space.

  By amplifying the resonant frequency of a resonant space created between two glasses, and changing the size of this space in real time by altering the distance between the glasses, my work engages the audience in the observation of a resonant frequency being modulated by the shifts of the size of the space in which this frequency is produced, in real time.

- *Music for Piano and Slow Sweep Pure Wave Oscillators* (1992)

  This is a piece for piano, and pure wave oscillators that produce tones whose frequency shifts upwards and downwards in slow sweeps. This piece explores the phenomenon of sonic interference through the creation of beats that are produced by an interaction between the pitches played on the piano and the tones.

  This principle is the point of departure for my composition *Auditory Rainbows*, for piano and resonating glasses. My piece extends this idea, and explores sonic interference through a system that produces pure tones whose frequency is modulated by the pitches played on a piano, through the interaction of these pitches with resonating glasses. The glasses isolate individual frequency components from the sounds of the piano, and amplify them to a feedback loop. In this way, *Auditory Rainbows* uses the ability of a space to filter an acoustic signal and amplify individual frequency components from this signal, and creates another metaphor for the relationship between the size of a space and the resonant frequency a sound will trigger in that space.

- Sato Minoru, aka m/s (b. 1963)

Sato Minoru is a Japanese sound artist whose work engages with the representation of physical phenomena and natural processes. As he explains 'his interests focus on physical phenomena and their reception, and his research and creative activities are explored in the form of exhibitions, multiples, performances and written text'[12]. On his personal website he mentions that he has a specific 'interest in a relationship between a description of nature and art representation, and he is creating art works per physical phenomena and various concepts'[13].

This approach has provided this study with a general research context for the representation of acoustic phenomena and their observation through the practice of sound art, however I found this conceptual framework to be too general. The present study focuses this framework to address the concept of an artistic representation of the intersection of sound with the physical space through the representation of elements of the physical space that can shape the evolution of a sound. Two works by Sato Minoru provide the research context for my installations *Tonality measured by distance* and *Observing density through standing waves* (refer to the video documentations on the DVD).

- *NRF Amplification* (2005)

  In this sound installation, Minoru uses closed vessels (glass tubes and glass vases) in order explore the natural resonant frequencies of a closed space. He amplifies this resonant

[12] Sato Minoru, 1999, *Sound Art – Sound as Media,* edited by Hatanaka Minoru and Nozaki Takeo, NTT Publishing Co. Ltd., p.34

[13] http://www.ms-wrk.com/AFrameset.htm - the personal website of the artist, last accessed 25/03/2013

frequency by placing a microphone on one side of each individual vessel and a speaker on the other, and instigating a feedback loop inside each vessel. Each individual feedback loop is then transmitted from one vessel to the other, and the whole system creates a complex feedback pattern.

This piece provides a research context for the representation of natural resonant frequencies in my sound installation *Tonality measured by distance*. In *Tonality measured by distance* the compositional method for this representation is the use of closed vessels (glasses), in combination with microphones and speakers that amplify the resonant frequency of these vessels. In my piece, the method Minoru follows is developed in the creation of a system that alters the size of a closed space, as well as the pitch of the resonant frequency of this space, dynamically. This dynamic alteration contributes with a new method of representation between a resonant frequency and the space in which this frequency is produced.

- *Observation of thermal states through a stationary wave* (2008)

  This is a sound installation in which Minoru explores a sound in two thermal states, hot and cold. The artist uses four glass tubes, and the same compositional strategy as in the previous work is employed in order to amplify the resonant frequency of these tubes: a microphone is placed on one side of the tube and is connected to a speaker on the other side of the tube. Two of the tubes are placed under constant lighting, so that the temperature inside these tubes is higher than in the other two tubes. This creates a pulsating tone: the feedback loop that is instigated inside the heated tube has a different frequency.

This piece provides a research context for my installation *Observing density through standing waves*. In my piece, I use a compositional method similar to the one Minoru follows. I am using tubes, with a combination of microphones and speakers in order to instigate a feedback loop inside the tubes. My piece however looks at the evolution of sound in mediums of different densities, rather the transmission of sound through mediums in different thermal states. My piece extends this approach and includes four individual densities that create a different soundscape and engage the audience in a different audio-visual experience.

- Toshiya Tsunoda (b. 1964)

Toshiya Tsunoda is another Japanese sound artist working with the physics of sound and acoustic phenomena. His work focuses on 'locating the unlocatable sound, defining the undefinable sonic event'[14]: the amplification of imperceptible sonic events. His practice steered this research projects towards the exploration of such sonic events, and the information these events can provide regarding our auditory perception and the relationship between sound and the physical space. Together with Minoru they formed a

[14] Brandon LaBelle, 2006, *Background Noise: Perspectives on Sound Art*, The Continuum International Publishing Group Ltd. p. 238

collective called *WrK* (1994 – 2006) that included artists Jio Shimitsu, Hiroyuki Iida and Atsushi Tominaga.

- *Standardisation of a Stationary Wave by a Sine Wave* (1996)

  This is a sound installation exhibited at the XEBEC Hall in Kobe, for about a month from the 18th November 1996. In this piece, Tsunoda focuses on a drone produced by a coffee machine in the lounge area of the venue. Using a loudspeaker he plays back sine tones in similar frequency to the drone of the coffee machine. This causes constructive and destructive interferences between the two sounds and creates a soundscape that changes according to the position of the audience in the space.

  This piece has not influenced my work directly, however it was crucial in the shaping of the conceptual framework of this study: the exploration and amplification of the sonic space between a sound source and the listener, and the elements that interfere with this sound until it enters the perception of the listener.

- Carsten Nicolai (b. 1965)

Nicolai is producing sound installations and compositions which he describes as being "influenced by scientific reference systems"[15] and he "often engages mathematic and cybernetic patterns, such as grids and codes, as well as error, random, and self-organizing structures"[3]. In 2009 and 2010, Nicolai published two visual dictionaries, the *Grid Index* (2009) and the *Moiré*

[15 & 13] http://www.carstennicolai.de/?c=biography - personal website of the artist, last accessed 20/09/2012

Index (2010). In the preface of the *Moiré Index*, Nicolai states: 'I appreciate the moiré effect because it challenges our optical perception. Its counterpart in the audio field – sonic effects caused by phasing and superposition of frequencies – has also been a valuable tool for me to explore sound production'[16].

The use of systems that produce self-organizing patterns as modes of representation has provided an important context for the present study. Most of the works produced as part of this project rely on systems that utilize scientific theories on acoustic phenomena in order to represent sonic evolution. In my work however I am engaging with these theories in different ways and from different perspectives. Two works by Carsten Nicolai provide the context for my sound installation *Refractions* (refer to the video documentation on the DVD).

- *Frozen Water* (2000)
- *Atem* (2000)

    Both of these sound installations utilize the visualization of sound in the form of wave patterns, through combinations of loudspeakers and flasks filled with water. In *Frozen Water*, two flasks of different sizes were used. The flasks were filled with water and were placed in front of loudspeakers that play very low sine tones. The wave patterns on the water in the smaller flask are more intense than the patterns in the bigger flask, and the artist presents

[16] Carsten Nicolai, 2010, *Moiré Index*, Gestalten, Berlin, preface

this phenomenon to demonstrate the polarities between order, chaos, movement, and stagnancy.

Atem follows a similar approach: nine loudspeakers are fitted on a wooden floor and two flasks of equal size filled with water are placed on the floor. The speakers emit a very low sine tone that is not audible to the audience, but is visualized through the wave patterns created on the surface of the water in the flasks. *Atem* explores the way vibrations transmit through objects, through the visualization of this vibration through wave patterns on water.

Refractions follows this compositional approach and creates a system with loudspeakers fitted at the bottom of plastic boxes that are filled with water. Similarly to the installations by Nicolai, *Refractions* creates a system that utilizes the interaction of sound with water as a way of representing this particular phenomenon. Rather than using water to visualize an acoustic vibration, *Refractions* is using an acoustic vibration in order to amplify the effects of the movement of the water on a sound that is being transmitted inside it: instead of visualizing sound through wave patterns, this installation amplifies wave patterns through a sine tone.

- Christina Kubisch (b. 1948)

Christina Kubisch is a German sound artist who ‘creates synthetic experiences in which embodied navigation become indistinguishable from musical form […] Sonically, what is “natural” and “artificial” are deliberately confused'[17]. The practice of Christina Kubisch is of interest to this study as in some of her works she is exploring the amplification of otherwise imperceptible phenomena through the use of technology: in 2003 for example, Kubisch initiated a project called *Electrical Walks*. In this project, the artist invites the audience to listen to electromagnetic interferences through the use of modified headphones.

The starting point for this research project has been the revelation of phenomena through the use of technology, however this project focuses on a very specific relationship between acoustic phenomena and the evolutionary process of a sound. From this starting point, this project develops different methods of representation.

- *Dreaming of a major third* (1997)

  This is an electroacoustic piece produced as part of a site-specific installation entitled *The Clocktower Project*, commissioned by the Massachusetts Museum of Contemporary Arts. In this piece, Kubisch uses music technology and techniques from the practice of electroacoustic composition in order to create a composition made from the bell sounds from a clock tower which is located amongst the museum buildings. In *Dreaming of a major third*, Kubisch focuses on the long resonant decay of the bell sounds and uses it to compose a piece that creates complex textures through the use of this resonance.

[17] Tara Rogers, 2010, *Pink Noises: women on electronic music and sound*, Duke University Press, p. 107

This piece provided the research context for my piece *Ripples* Audio CD 1, Track 1). One of the first observations in this study of an element that can interfere with the evolution of a sound occurred through the use of a similar sound material to Kubisch: the resonant decay of a clinking glass. Just like *Dreaming of a major third*, *Ripples* uses the resonance of a sound through several electroacoustic techniques, such as time stretching, pitch shifting, and repetition (delay). *Ripples* however is not focused on the representation of the natural resonance of the sound, but uses this resonance as a vehicle for the exploration of the effects of sonic refraction on this resonance.

- Jonty Harrison (b. 1952)

Jonty Harrison is a British composer of electroacoustic music and his work explores audio manipulation technologies and sound diffusion. Harrison is the director[18] of the Birmingham Electroacoustic Studio (BEAST), located at the university of Birmingham. Harrison is particularly interested in electroacoustic composition and the way a sound can be diffused in space through systems of multiple loudspeakers.

Aesthetically, his work is located within the practice of electroacoustic composition. This research project engages with the use of music technology for the perception, documentation and presentation of phenomena of interest. a\An exploration of the practice of electroacoustic composition was crucial in providing the tools for the exploration of the phenomenology of sound.

[18] Michael Kennedy and Joyce Kennedy, 2007, *Oxford Concise Dictionary of Music* (fifth edition), Oxford University Press, p. 334

However, this project could not be confined to the field of electroacoustic composition, as it needed to expand in order to include several methods of representation of such a multifaceted concept as the aural evolution.

- *Klang* (1982)

  Klang is an electroacoustic piece that uses the resonant decay, as well as the percussive character, of sounds produced by metal pots when they are being hit. Through the exploration of the resonance of a sound using technology, Klang provides the research context for my piece *Ripples*. *Klang*, however, focuses on the use of technology in order to introduce variations to this resonance and manipulate it digitally. In contrast, *Ripples* does not engage with the use of music technology in order to manipulate a sound but rather to give emphasis to specific elements of a sound that demonstrate an aspect of the evolutionary process of a sound.

The following chapters explain the creative process for the production of each work, and include a more detailed analysis of the aforementioned practitioners and their contributions to this project. Each chapter looks at a specific work that was produced as part of this study in terms of its concept, methodology, research context, and materials. Each of the works falls under a specific conceptual framework, either the relationship of sound with the medium in which this sound is being transmitted, or the relationship of sound with the size of the space in which this sound is being produced. In the following chapters however, for reason of clarity on the whole creative process, the pieces are presented in chronological order. In the Conclusions section, the works are presented according to their conceptual frameworks.

2. Ripples (2008)

An Electroacoustic composition
Audio CD 1, Track 1

2.1 Concept

Ripples is an electroacoustic composition and the first in a series of works that explore the relationship between sound and the medium through which it travels. This piece arose from a sound that exposes the effects of sonic refraction in everyday life: the sound of clinking glasses. When two glasses filled with liquid hit each other during a toast at a party, a wedding, or simply a family dinner, the sound that is produced is shaped by the way the liquid moves inside the glass, and the way in which soundwaves reflect inside the glass. As the sound moves from the liquid to air, the direction of the sound wave changes, and of course affects the way in which the soundwave reflects inside the glass. The soundwave also reflects back onto the surface of the moving water, resulting in subtle fluctuations in the frequency spectrum of the sound. This phenomenon will be demonstrated later in the Methodology section through the analysis of the sound of the glasses. *Ripples* aims to emphasize and amplify this phenomenon, and reveal its harmonic and rhythmic qualities.

Ripples was selected for inclusion in an online collection by the AND Network: a vast network of sound artists and composers that are based in various locations around the world. The collection is entitled *SoundLAB VI: sound-pool, a tool for imagination* and is curated by German new media artist and curator Wilfred Agricola De Cologne. The theme for this edition of the collection, edition VI, was “sound as a tool for imagination” and was released in December 2009. This edition (as well as other editions of the collection) is available at:

http://soundlab.newmediafest.org/blog/?page_id=185

This edition was also selected for participation at the FILE Hipersonica Festival in Sao Paolo, Brazil from the 28 July until the 30 August 2009. Hipersonica is part of the FILE Electronic Language International Festival.

2.2 Methodology

This piece is the direct result of the observation, documentation, and analysis of the sound of the clinking glasses. I first observed this sound while washing a big metal cooking pot. When the pot was half-filled with water and I accidentally hit it on the metal water tap, it produced a metallic sound with a long, resonant decay and a subtle vibrato. I started experimenting with the metal pot, filling it with different amounts of water and hitting it while trying to agitate the water inside it. The vibrato of the resulting sound was related to the movement of the water inside the metal pot: the more the water was startled, the more intense the vibrato would become.

While trying to understand what was causing this phenomenon, I imagined the journey of the sound as it travelled through the pot: the sound was produced on the sides of the pot when they came in contact with the metal tap, and was being reflected around the pot. This sound was also reflecting on the surface of the moving water: as this surface was moving, the distance the sound had to travel until it reflected on the sides of the pot was constantly changing. As will be demonstrated in the next chapter of this thesis, the size of the space in which a sound is produced can shape the fundamental frequency of this sound. I thought that this was one of the factors that created the fluctuations in the frequency of the sound.

The other factor was the phenomenon of sonic refraction: some instances of this sound were produced under the surface of the moving water, and travelled across from underneath the water and into the air. When a sound wave is transmitted through two mediums of different densities, in this case air and water, the phenomenon of sonic refraction occurs: the direction in which the sound wave is travelling changes. The fluctuations in the fundamental frequency of the sound are the result of sonic refraction, and the way sound reflects inside the glass and on the surface of the moving water.

I wanted to re-create this phenomenon in the studio in order to record and analyze it, and see which elements of the structure of the sound were affected. This time I thought I would see if I could replicate the sound observed with the metal pot, through the use of beer and wine glasses of different sizes. This decision came after thinking what would be the most familiar sound to an audience. The sound of clinking glasses is a sound everyone comes across in various situations, and I thought it would be interesting to explore the behaviour of such a widespread, yet perhaps overlooked, sonic interaction.

I was hitting the glasses gently with a drumstick while holding them as close to the microphone as possible. While hitting the glasses, I was also rocking them back and forth in order to startle the water and recreate the effect that was originally observed with the metal pots. I used wine and beer glasses of different sizes, and recorded several takes with different amounts of water in each glass. I then used Adobe Audition CS4 for Windows in order to analyze the sounds: as soon as a sound is loaded, Audition performs a Fast Fourier Transform analysis and displays the dynamic range and the frequency spectrum of the sound:

Figure 1: FFT Analysis of the sound of a wineglass

In Figure 1 we can see two areas: the smaller area on top displays the sound wave in green and shows the dynamic range of the sound. The larger area at the bottom - in red, yellow and purple - shows the frequency range of the sound and the loudest harmonics. The colour range between purple and yellow represents the loudness of each harmonic, with yellow being the loudest. In the case of this sound, the loudest and longest harmonics are between 1 kHz and 4 kHz. Figure 1 also reveals that the vibrato on the sound is caused by subtle fluctuations in the frequency of the loudest harmonics of the sound wave.

While working with the sounds, listening back to them and observing the fluctuations in their harmonics, I started thinking about ways in which I could magnify this effect and make it easy to perceive. I wanted to increase the duration of the effect so I started time - stretching the sounds, aiming to give emphasis to the fluctuations in the frequency spectrum. I used time – stretching as a sort of a magnifying glass that would allow me to give a closer look at the behaviour of the sound when the liquid was startled. As I was listening to this everyday sound without the visual counterpart of the glass and the water being startled inside it, my attention was focused on the details of the sound being produced and the fluctuations on the frequency.

The separation of a sound from its sound source is the practice of Acousmatic Listening and dates back to Pythagoras. In his chapter on Acousmatics[19], Pierre Schaeffer informs us that:

> '*Acousmatic*, the *Larousse* dictionary tells us, is the: "*Name given to the disciples of Pythagoras who, for five years, listened to his teachings while he was hidden behind a curtain, without seeing him, while observing a strict silence*." […] The *Larousse* dictionary continues: "*Acousmatic, adjective: is said of a noise that one hears without seeing what causes it*." This term […] marks the perceptive reality of sound as such, as distinguished from the modes of its production and its transmission.'

Even separated from its source, the sound can still be familiar and we might be able to recognize it. However, when a sound is separated from its source it

[19] Pierre Schaeffer, *Acousmatics*, re-published in *Audio Culture: Readings in Modern Music* (2006), edited by Christoph Cox and Daniel Warner, The Continuum International Publishing Group Ltd, pp. 76-77

becomes an autonomous sonic entity: without the visual distraction of the source of the sound, we can focus more on the character and qualities of the sound.

My aim was to present the sound of the clinking glasses to an audience in an Acousmatic setting focusing their attention on the phenomenon of sonic refraction and its effect on the sound of the glasses, while also creating an immersive sonic experience. I also thought that the sound of the clinking glasses is a regular occurrence in our lives, which makes it recognizable and good material for the demonstration of an acoustic phenomenon in an everyday situation. I used the collected material in order to compose an Electroacoustic piece that would focus on the qualities of this intriguing phenomenon. My aim was to present some of the harmonic, as well as the rhythmic qualities this effect has on a very familiar everyday sound.

2.3 Structure

This composition as a whole is a process of zooming in and out of the sound of the clinking glasses. The purpose of this process is to look into both the microcosm and the macrocosm of the acoustic phenomena that operate during the interaction of sound with the medium in which it is being produced, as these phenomena are manifested through the sound of the clinking glasses. As mentioned earlier the technique of time – stretching was used as a means of zooming into the sound of the clinking glasses, through the prolongation of the duration of the sonic event.

The piece begins with the exploration of the microcosm of this sound, and presents the sound to the audience through a sort of a magnifying glass.

The sounds that were collected during the recordings were time – stretched, and used as means to create a continuous harmonic texture. The duration of the original sounds was no longer than one and a half seconds, and each of the sounds was time – stretched to a final duration of no longer than fifteen seconds. The decision on the amount of time – stretching was based on the duration of the resonance of the original sound: the longer the original resonance was, the more it could be prolonged. As the frequency range of the original sounds was quite limited, some of the time – stretched sounds in this section were also pitch shifted in order to create a more complex and engaging harmonic texture.

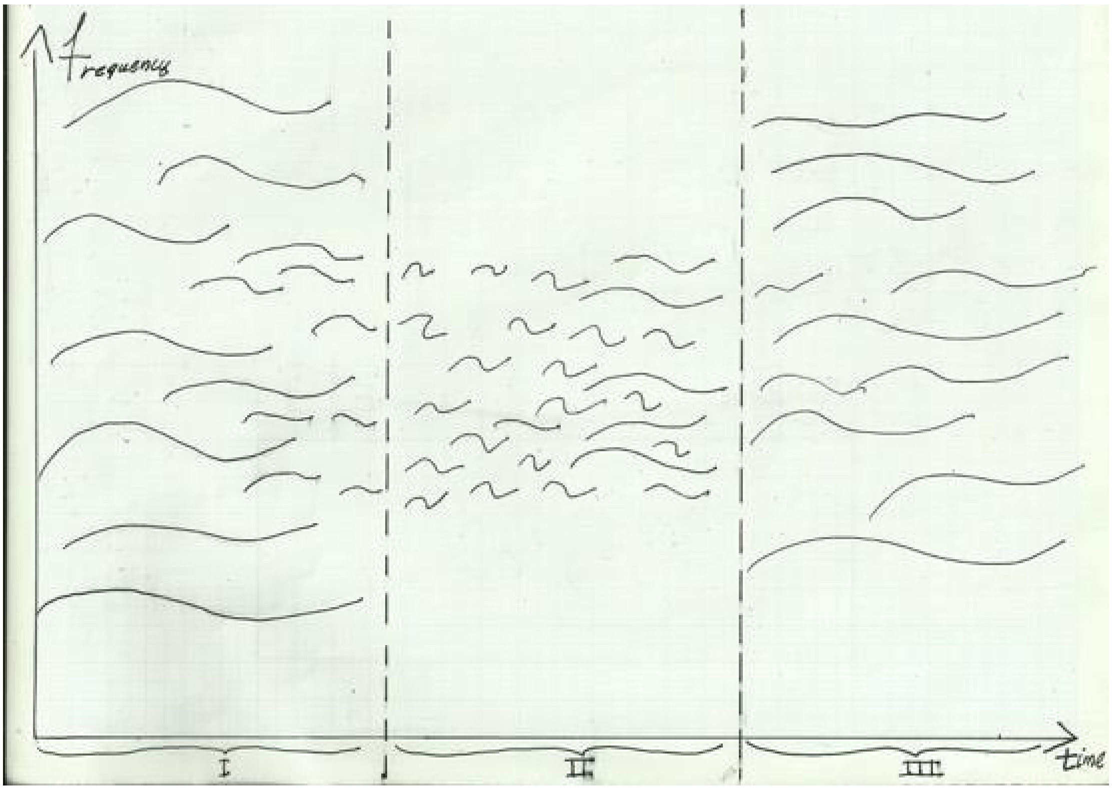

Figure 2: Diagram of the structure of *Ripples*

Slowly the piece zooms out and looks at the macrocosm of the sound, and how it is heard in its original form. To achieve this, the continuous harmonic texture gradually breaks up in order to give way to a more gestural texture composed from the original recordings of the sounds. The percussive sounds of the clinking glasses are used to create different rhythmic patterns. Several delay effects, such as Spectral or Tape Delay, are used to add some variety to these rhythmic patterns, however all of the recorded sounds are presented for the biggest part in their original form. After this brief look into the macrocosm, the piece zooms into the microcosm for one last time before it arrives to an end.

2.4 Research Context

The research context for this composition is defined by two pieces from the territory of electroacoustic composition: *Klang* (1982) by Jonty Harrison and *Dreaming of a major third* (1997) by Christina Kubisch. *Klang* is an electroacoustic composition made primarily with sounds from metal pots produced by hitting and scratching the pots with their lids, as well as various other metallic sounds that were collected by the composer over the years[20]. Harrison describes these sounds as 'sharp, metallic attacks with interesting resonances and rich harmonics'[3]. In this piece the composer emphasizes the long resonant decay of the metallic sounds, and sometimes enriches the harmonics that are produced through the use of several digital processes such as frequency modulation, repetition, time – stretching etc.

[20 & 3] Jonty Harrison's program notes on *Klang*
Audio CD *Collection I: Kang* 1996 NMC Recordings Ltd, booklet p. 3

Harrison first presents the sonic matterial of the piece in its original state, with emphasis to the long resonant decay of the metallic sounds. For the biggest part of the introductory section (00:00 – 03:00) this resonance is emphasized with various digital processes such as delay and frequency modulation: at 00:21 for example, a steady delay prolongs the duration of the resonance and emphasizes its harmonic qualities. At 00:40 the same delay is used once more to emphasize the resonance of the sound from a different pot.

From the third minute onwards, the processing of the sounds becomes more intense: at 03:04 the decaying resonance of the metallic sound is processed and prolonged with an effect called GRM Resonance: this effect creates an artificial, bell – like resonance which can be processed with several band pass filters and frequency modulators. In this case this effect is used to prolong the decay of the metallic sounds, and process this decay in order to use it as a basis for the creation of an electronic soundscape. Gradually, the transformations of the sounds become more intense and complex, and at 04:09 the piece dissolves to a digital soundscape: the resonance of the metallic sound is stretched, and the sound of the scraping of the metallic lids is looped and pitch shifted in order to create a low frequency drone that vaguely resembles the original sound. Finally, at 07:00 the electronic soundscape dissolves and the sounds return to their original form until the end.

Ripples is composed out of an interest to follow a similar approach, and focus on the resonance of the sound of the glasses as a vehicle for the exploration of the phenomenon of sonic refraction and the relationship of sound with the medium in which it is produced. In order to magnify this relationship, I stretched the sounds and turned the small fluctuations in the frequency of the resonances into long glissandi. Some of these long glissandi were also transposed in order to produce more complex harmonies.

However, *Ripples* is not an exploration of sonic transformation through the use of digital technology. The processing was very limited and the development of the piece does not rely solely on digital processing. Instead, the piece exposes the magnified version of the sounds, followed by the original version presented as rhythmical events, which in turn leads back to the stretched sounds presented at the beginning (refer to section 2.3 on structure). In contrast to *Klang*, *Ripples* begins with the magnified sounds, briefly presents them in their original form, and ends with the same magnified sounds in order to emphasize the effects of sonic refraction on the sound of the clinking glasses.

The second piece that defines the research context of *Ripples*, *Dreaming of a major third*, is a composition by Christina Kubisch. *Dreaming of a major third* is part of the *The Clocktower Project*: a site-specific sound installation commissioned by the Massachusetts Museum of Contemporary Arts (MASS MoCA) in North Adams, Massachusets. In this installation Kubisch placed solar panels on and around the clock tower located at the museum. These panels send information about the position of the sun and the amount of sunlight to a computer, which uses this data to arrange samples from the clock tower bells in a composition that is played back inside the space.

In her piece, Kubisch focuses on the resonant decay of the bell sounds and creates complex textures by overlaying their resonances. Since the very beginning the composer emphasizes the resonance of the sound: the very first sounds of the piece are allowed to decay naturally, and the duration of their decay is ten seconds. This process continues until 00:29, when the composer fades the sound of a bell in so that only the resonance after the metallic attack is heard: this way the harmonic qualities of the resonance are emphasized, and used to form organ – like sounds.

These sounds are pitch shifted[3] and combined in order to create textures of beats produced by sonic interference, as well as different harmonic progressions. An example of beats is heard from 01:19 to 01:33: two resonant sounds of the same pitch enter at slightly different times and create beats due to the difference of phase between them. Slightly later at 03:12 a minor chord is formed by the over layering of three sounds with different frequencies. This layering results in the creation of complex beats produced by the interference between the different overtones of the sounds.

This informed my approach in the opening and closing sections of *Ripples*: the aim was to use the glissandi produced by the stretched sounds from the glasses in order to create complex harmonic textures, that further affect the overall timbre of the sound through the beats created by the interference between the gliding overtones of the sounds. While Kubisch retains and emphasizes the natural decay of the bell sounds, I also time – stretched the sounds in order to prolong their original decay. Furthermore, unlike *Dreaming of a Major Third*, I am not focusing on the natural resonance

[3] Christina Kubisch, *Dreaming of a major third* Audio CD 1997, MASS MoCA, back cover

of the clinking glasses, but on the way an acoustic phenomenon manifests through this resonance. The rich resonant decay of the sound of the clinking glasses is used as a vehicle for the exploration of the physical evolution of sound.

3. Tonality measured by distance (2009)

A sound installation

3.1 Concept

Tonality measured by distance is a kinetic sound installation that explores the relationship between sound, and the size of the space in which this sound is produced. We can perceive information about the size, or the shape, of the space we are in through sound. The frequency and dynamics of sound can be modulated from the reflection of this sound around the space. The distance a sound has to travel before it reflects on a surface for example determines the base frequency of the reflected sound. This modulation can enable a sonification of this space: it provides us with aural cues so that we can construct a 'sonic' map of the space we are in in our brain[21]. Our auditory experience of a space allows us to assess the volume and characteristics of that space.

This sound installation is the result of a process of experimentation with the natural resonant frequencies of a space. Natural resonant frequencies of a space are the frequencies that this space will amplify if a sound is produced inside it. These frequencies depend on the size of the space, and the way sound is diffused inside it. Physician and physicist Hermann Von Helmholtz (1821 -1894) was already applying this principle to his research in acoustics in the Eighteenth Century, and in the 1860s he invented the *Helmholtz*

[21] Olivier Warusfel from IRCAM demonstrated through experiments that we are capable of constructing a sonic map of the space we are in in our brain: our brain uses the information about the directionality and distance of the sounds that might exist in the space, in order to orientate in that space. In his experiments he demonstrated how blindfolded participants managed to locate a fixed spot within a space, through the use of hearing and with the help of three fixed sound sources that provided reference points for the brain to calculate the position of the desired spot in relation to these sources. These experiments were presented at a symposium on auditory perception and its relation to the other sensory modalities, in the framework of the EarToy project. The symposium was held at IRCAM in Paris, France on the 11 November 2009.

Resonators[22] (Figure 1). These resonators are hollow spheres, open on both ends, and are designed in different sizes in order to isolate individual frequencies from the spectrum of the soundscape of a space. The listener can place his or her ear on one end, and hear the resonant frequency that is being isolated.

Figure 1: The Helmholtz Resonator

This piece is created as a metaphor for this intriguing relationship: it is an audio-visual sculpture that uses this phenomenon in order to produce a soundscape that changes with the distance between two resonating objects. The form of this work derived from imagining one of the Helmholtz Resonators cut in half, and able to isolate different frequencies by changing the distance between the two halves of the Resonator. A system (Figure 2) is made using a wineglass and a small candle glass. The candle glass is attached via a metal bracket to a windscreen wiper motor, held above the wineglass on a wooden base. As the windscreen wiper motor is turning slowly, the candle glass is hovering in a circular motion, and continuously moves further from,

[22] Hermann Von Helmholtz, 1895, *On the sensations of tone as a physiological basis for the theory of music* (third edition), Longmans, Green, and Co., p. 43

and closer to, the wineglass. The distance between the two glasses varies between 1mm and 12cm.

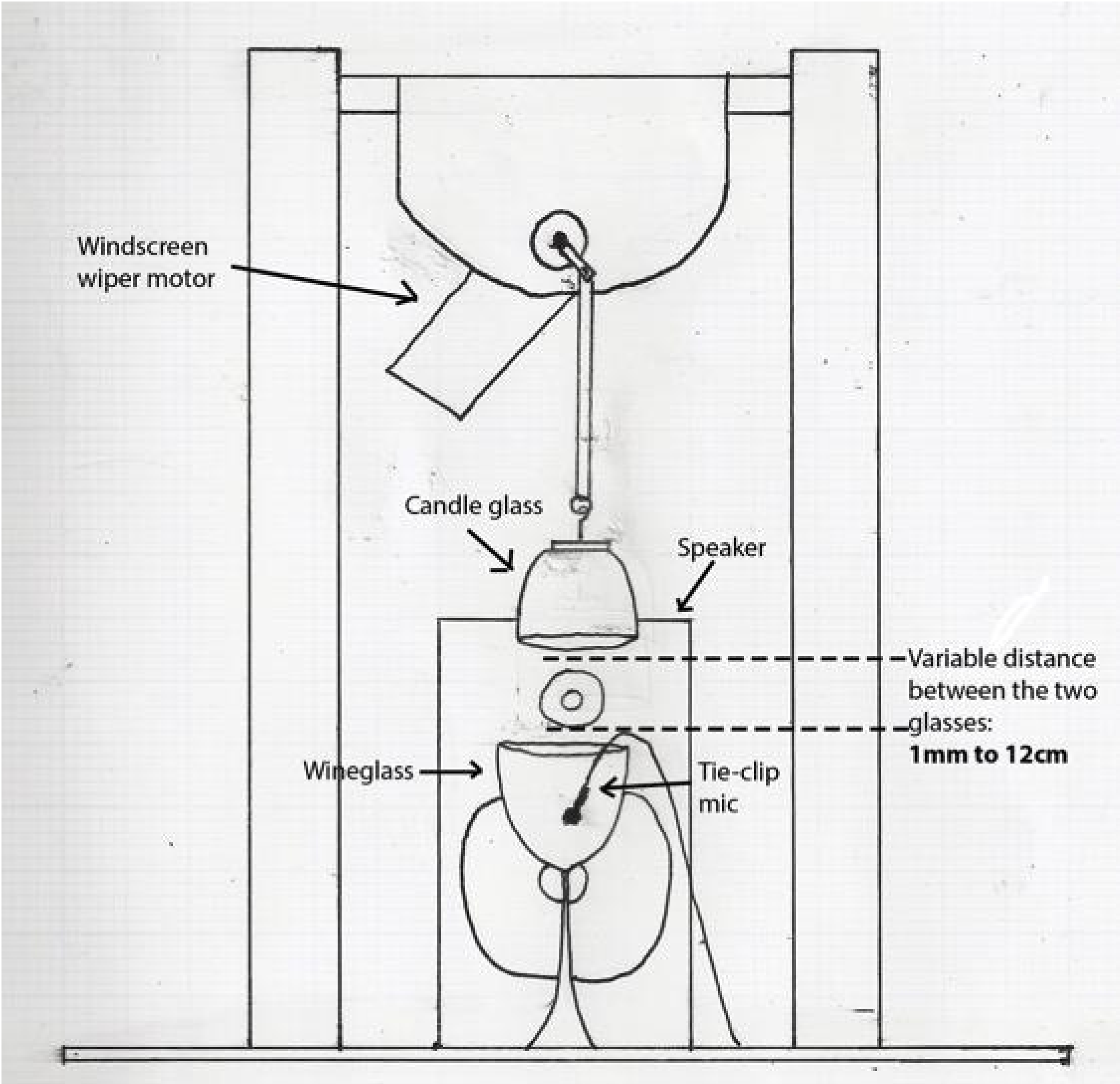

Figure 2: The resonating system

A tie-clip microphone is placed inside the wineglass, and is connected to a loudspeaker through a laptop that runs Logic Pro and acts as a mixer. The loudspeaker is placed directly behind the wineglass, so that a feedback loop is instigated when the volume of the microphone is turned up. The pitch of this feedback loop depends on the size of the wineglass: the smaller the wineglass is, the higher the pitch of the resulting feedback. The three resonating wineglasses that were used in the production of the work, shown in Figure 3, resonate at 1000Hz, 600Hz, and 500Hz respectively.

Figure 3: Sonic Art Oxford, Jacqueline Du Pré Music Building, 2 & 3 April 2009

As the distance between the candle glasses and the wineglasses is continuously altered with the help of the motors, the frequency of the feedback loops changes. The motors are all set to the lowest speed possible, and they are not synchronized with each other, causing the tones to change pitch at different times. The work was exhibited in two different forms at Sonic Art Oxford, an event organized by the Sonic Art Research Unit at the Jacqueline Du Pré Music Building in Oxford from the 2 – 3 April 2009, and at The Cube in Bristol on the 3 May 2009.

3.2 Methodology

I started practically experimenting by trying to record natural resonant frequencies in glasses of different sizes. Glasses can isolate individual frequencies from the spectrum of a soundscape similarly to the Helmholtz Resonators: they are small closed spaces, and isolate an individual frequency according to their size. My practical experiments started in one of the studios at Oxford Brookes University. A very low hum from the pipes of the air conditioning was present in the studio, so I thought I would try to record the soundscape that was created in the room by this sound through glasses of different sizes (Figure 4). I placed tie clip microphones inside the glasses and placed them underneath the sound source, trying to record one glass at the time. Tracks 1 and 2 on Audio CD 3 are recordings of this sound without the glass (Track 1), and through the glass shown in Figure 4 (Track 2).

Figure 4: Recording the sound of the air-condition through a glass.

While recording different takes of this sound, I turned the volume of the microphone up to the point where the sound began to feedback from the speaker to the microphone, and produced a loud tone that peaked at 0db. I observed that I could alter the frequency of the resulting sound by moving my hand further from, or closer to, the glass as shown in Figure 5. The glass in this image for example (one of the glasses used during the experiments) resonates at 1000Hz. As I was moving my hand closer to the glass, the pitch of the feedback was getting lower. When my hand was at the lowest point (about one millimeter above the glass) the frequency of the feedback loop was 500Hz. As I was moving my hand away from the glass, the frequency was rising until it returned at 1000Hz. My hand could go as far as 12cm above the glass until it stopped affecting the frequency of the feedback loop, which is what informed my final decision on the maximum length of the distance between the candle glass and the wineglass.

Figure 5: Controlling sonic feedback using a microphone and a glass

My hand acts as a sort of a physical extension of the glass: by moving my hand closer to, or further from, the glass I am changing the way sound reflects in, and around, the glass. This alters the frequency of the feedback loop that is created between the microphone and the glass, enabling me to physically interfere with the circulation of sound.

Initially, I tried to use this system as a performance instrument. At first, I recorded an improvisation using four glasses with microphones inside them in the way shown in Figure 4, entitled *4 Small Well-Tempered Spaces* (Audio CD2, Track 3). This improvisation was not published or performed in front of an audience, and it was purely made in order to familiarize myself with this concept. Other uses of this system have been also explored, for example its combination with electronic sounds that resulted in two versions of an unpublished recording entitled *A white noise mass* (CD2, Tracks 1 and 2). These recordings eventually led to the creation of the work *Auditory Rainbows*, and will be dealt with in detail in the relevant section of this thesis.

I wanted to take this concept further and develop it into a sound installation. Informed by the way I could control sonic feedback through the movement of my hand, I started thinking of ways in which I could construct a system that would manipulate the resonant frequencies of small vessels using different types of body movement. My first idea was a sound installation that would respond to the audience’s movement in a space and I started exploring ways in which such a system could be constructed. I thought of placing the glasses with the microphones on a wall and the speakers directly in front of them, so that the audience would act as the physical extension of the glasses and change the resulting feedback with their movement in the space.

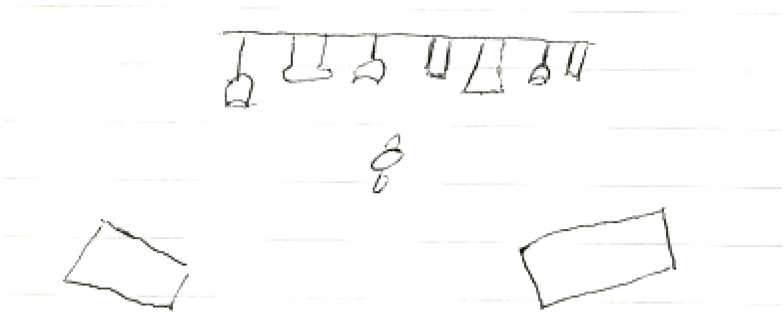

Figure 6: Glasses with microphones inside them are fixed on the walls with speakers in front of them.

I conducted several experiments to see if such an approach would work. I took vessels of different sizes, put a tie clip microphone inside each vessel, and placed all the vessels in a row. Opposite this row I placed the loudspeakers, and connected them to the microphones. I turned the volume up to the point in which the sound started feeding back, and started walking between the vessels and the speakers, and moving around the space. My movement however did not affect the frequency of the feedback in any great way. A few slight changes in the frequencies of the feedback tones occurred, but they were very scarce and intermittent.

I tried different setups, changing the positions of the speakers and the glasses around the space, but the result was always similar. After several trials I abandoned the idea of the frequency being shaped by the movement of the audience, and started thinking about going a different direction. I started thinking about constructing a mechanism that would work similarly to the way in which I was physically changing the feedback tone by moving my hand closer to, and further away from the glass. This mechanism would involve a wineglass with a tie-clip microphone inside, placed in front of a speaker. The idea was to have another object moving up and down on top of the wineglass.

This object should fit like a cap on the wineglass. As mentioned in section 3.1, the Helmholtz Resonators informed the decision on the selection of the object. I wanted to create a Resonator whose size would be variable, and would change the frequency of its resonance by changing its size. I then thought about using two glasses, one on top of the other, so that both glasses would form one Resonator cut in two pieces. I experimented with several different glasses, moving them up and down above a wineglass with the microphone inside it. The result on the frequency of the feedback tone was the same as when I was using my hand, so I thought about attaching candle glasses on windscreen wiper motors above the resonating glasses. I then started making some drawings of a system that would utilize windscreen wiper motors in order to change the distance between two glasses (Figures 7 and 8).

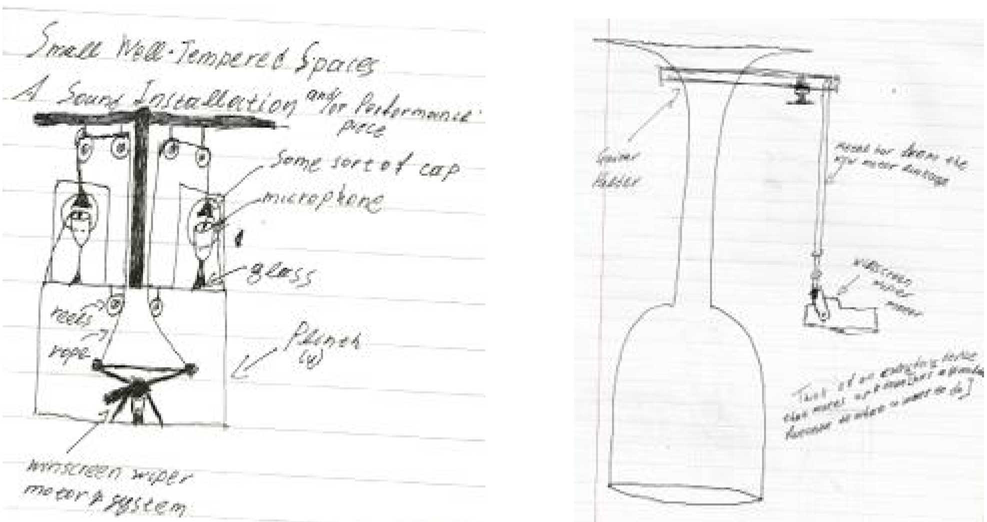

Figure 7: The first sketches of the work

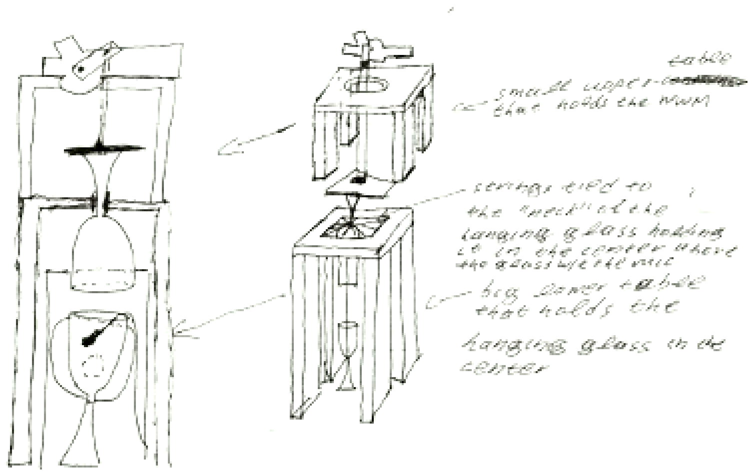

Figure 8: A more conclusive sketch of the work

At first, all the designs seemed to be needlessly complicated and involved systems of strings passing through rails, or complicated bases holding the wine glasses upside down. However, I thought that I should keep it as simple as possible, so I constructed a system with the motor attached on a metal bracket above the wineglass, held by a wooden base. A small candle glass was attached via another bracket to the motor, and was hovering in circular motion above the glass with the microphones inside it (Figure 9). This system was able to produce two different tones.

Figure 9: The work near its final form.

At this point I had to make an important decision regarding the number of glasses to be used; I was thinking whether I should use more than one, and if so, why and how many. The central aim of this project is to represent the tonality (or base frequency) of a sound as it is modulated by the natural tendency this sound has to change its frequency according to the space it inhabits. I decided to use three resonators at first, representing a tri-chord whose notes are tuned by sound's natural behaviour, allowing the chord to shape itself. When the project was finished however, I realized that there was one issue: the resulting sound was too loud, and I could not turn the volume down because I would loose the effect that the changes in the distance between the wine glass and the candle glass produced. I decided that I have to be flexible in terms of the amount of resonators I was going to use. As I was also interested in how this project will work in different spaces, the work had to adjust to the size of the space where it was exhibited.

During the exhibition at Sonic Art Oxford for example, the work was placed in a fairly big and reverberant space. It was exhibited in the foyer of the Jacquilene Du Pré Music Building, at St. Hilda's College in Oxford. This foyer is a long corridor, about four meters wide and ten meters long. The outer wall is made out of glass windows (similarly to a conservatory). As this space was fairly big, and very resonant due to the glass windows, all three resonators were used. In Bristol the space was considerably smaller: the piece was exhibited at the foyer of The Cube. It was a relatively small room, about three meters wide and five meters long. I decided to use only two glasses in this occasion, as three glasses were too loud for such a small space.

Another issue that came up was controlling the feedback. I needed to make sure that the feedback would not overload the speakers, so the sound was processed with a limiter via a laptop using Logic Pro. The limiter allowed the sound to evolve to a safe level, without interfering with the effect produced by the changes in the distance between the glasses. As the frequency of the feedback was changing between two tones with the movement of the candle glasses, it produced another very short tone on occasion. This tone was too short for an observer to perceive easily, so I decided to add a short delay to the set up, of about two repetitions per second; by adding this delay I have prolonged the existence of this randomly occurring tone, making it easier for the audience to hear when, and if, it would appear.

Figure 10: Sonic Art Oxford, Jacqueline Du Pré Music Building, 2 & 3 April 2009

Figure 11: Depth of Field, The Cube, Bristol, 3 May 2009

Figure 12: Depth of Field, The Cube, Bristol, 3 May 2009

3.3 Research Context

Two works that deal with the intrinsic relationship between sound and space in very different ways define the research context of *Tonality measured by distance*. The first piece is *I am sitting in a room* (1969) by composer Alvin Lucier. In this piece, Lucier is using two tape recorders in order to overlay recordings of his voice interacting with the space. The score[23], a text outlining the instructions for the realization of the piece, reads as follows:

> **I am sitting in a room (for voice and electromagnetic tape, 1969)**
>
> Necessary Equipment:
> One microphone, two tape recorders, amplifier, and one loudspeaker.
>
> Choose a room the musical qualities of which you would like to evoke. Attach the microphone to the input of tape recorder #1. To the output of tape recorder #2 attach the amplifier and loudspeaker. Use the following text or any other text of any length:
>
> I am sitting in a room different from the one you are in now. I am recording the sound of my speaking voice and I am going to play it back into the room again and again until the resonant frequencies of the room reinforce themselves so that any semblance of my speech, with perhaps the exception of rhythm, is destroyed. What you will hear, then, are the natural resonant frequencies of the room articulated by speech. I regard this activity not so much as a demonstration of a physical fact, but, more as a way to smooth out any irregularities my speech might have.

[23] *Alvin Lucier: Reflections*, 1995, Music Texte, p. 312

Record your voice on tape through the microphone attached to tape recording #1. Rewind the tape to its beginning, transfer it to tape recorder #2, play it back into the room through the loudspeaker and record a second generation of the original recorder statement through the microphone attached to tape recorder #1. Rewind the second generation to its beginning and splice it onto the end of the original recorder statement on tape recorder #2. Play the second generation only back into the room through the loudspeaker and record a third generation of the original recorded statement through the microphone attached to the tape recorder #1. Continue this process through many generations.

All the generations spliced together in chronological order make a tape composition the length of which is determined by the length of the original statement and the number of generations recorded. Make versions in which one recorded statement is recycled trough many rooms. Make versions using one or more speakers of different languages in different rooms. Make versions in which, for each generation, the microphone is moved to different parts of the room or rooms. Make versions that can be performed in real time.

Lucier records himself reciting a text explaining his activity on one recorder, and then he is playing it back in the space while recording it on the other recorder. By repeating this process several times, he amplifies the resonant frequencies of the room and what is left on the tape is the way his voice resonates in the room: a complex layering of bell-like resonances that follow the envelope of his voice. This piece pointed me to the direction of natural resonant frequencies of a space, and one way these frequencies can be revealed and amplified. The idea of creating a system that dynamically alters a small space, and at the same time amplifies the resonant frequencies of this space, started to emerge form the research I did on *I am sitting in a room* and on the Helmholtz Resonators.

Another work that provides a context for *Tonality measured by distance* is a sound installation by Japanese sound artist Sato Minoru entitled *NRF Amplification* (2005). In this piece, Minoru uses five different vessels: two long glass tubes and three glass vases. He places a microphone on one end, and a speaker on the other end of each vessel. As a result, a feedback loop is produced inside the vessels. He then transmits this feedback loop from one vessel into the other, creating a complex feedback pattern.

Figure 13: *NRF Amplification*, 20-22 May 2005, CCNOA, Brussels
(© Minoru Sato)

This piece (alongside the practical experiments detailed in the Methodology section) pointed me to the direction of using small vessels with microphones inside them in order to produce and manipulate sonic feedback. The central mechanism in *NRF Amplification* is a combination of vessels of different sizes that isolate a different resonant frequency according to their size. *Tonality measured by distance* takes this idea forward by exploring a way in which the size of each resonating mechanism can continuously change, and modulate the resonant frequency that is being amplified. This way, I am using this technique in order to create a metaphor that demonstrates the link between a resonant frequency, and the size of the space in which this frequency is transmitted, by altering the size of this space in real time. In my piece however, I follow a slightly different approach: the speaker is placed outside the glass, so what is affected in this case is the way the feedback reflects inside, and around, the glasses that are steady, and the glasses that revolve with the help of the motors. The feedback reflects between these glasses, and it is affected by the changes in the distance between them.

3.4 Materials

The sonic material for this piece is the feedback created from the microphone and the speaker. Sonic feedback is an element used often in rock music ever since the invention of the amplifier; from performances by guitar players in the 1960s and 1970s such as Jimmy Hendrix – perhaps his most notable being the performance of the *Star Spangled Banner* in Woodstock in 1969 – and Jimmy Page, to more contemporary musicians such as Eddie Van Halen, Joe Satriani, Steve Vai, Sonic Youth, Battles and several other rock and heavy metal bands. Sonic feedback also found its way in the art galleries and concert halls with artists and composers such as Sato Minoru, Toshiya Tsunonda, Alvin Lucier, and others.

In the case of *Tonality measured by distance*, sonic feedback was used primarily for practical purposes: feedback is basically a sine tone and an ideal material for the observation of this phenomenon. Both *NRF Amplification* by Minoru and *Tonality measured by distance*, demonstrate that the frequency of sonic feedback can be determined by the size of the space inside which it reflects. Therefore, sonic feedback is an ideal element to communicate the idea behind the work to the audience.

The other reason for the choice of this specific sonic material is that I found the overall sonic outcome to be in harmony with the visual element of the glasses on the motors gently spinning around, above the glasses with the microphones inside them. The changes in pitch that occurred corresponded to the movement of the glasses, and this further supported the conceptual basis of the work: the tonality of the soundscape was changing as the distance between the glasses was altered. This conveyed the concept of the work clearly to the audience while also producing an immersive audio-visual experience.

The glasses were initially chosen because they were very good “conductors” of sonic feedback: they acted like the Helmholtz Resonators and amplified specific frequencies from the soundscape of the spaces in which the work was placed, and with the help of the microphones and the speakers these glasses were able to produce different tones. After several sizes and types of glasses were used, I chose the glasses whose tones were closer in pitch; this way the tones interfered with each other producing various beats and overtones, composing a more interesting soundscape.

When the work arrived at a more conclusive stage (figures 10 – 12), the glasses also took another significance: I was intrigued by the fact that I could amplify the resonant frequencies of these familiar, everyday objects. I thought that these frequencies always exist in the glasses and they are always altered when we are using them; for example when we are drinking from the glasses and bring them closer to, or moving them away from, our mouth we are altering the resonant frequencies in a similar way *Tonality measured by distance* alters the tone of the resulting feedback loops.

The bases that hold the motors are made out of recycled wood, which was lying around at the university, and I liked the idea of recycling it and of not letting it go to waste. However, the reason for this decision was also practical as wood is very easy to manipulate. The bases were painted black because the speakers I used when the piece was first exhibited were also black, so this gave coherence to the work. Also, black is a fairly neutral colour that can work in almost any space the work would be exhibited. Finally, the windscreen wiper motors were also chosen for practical reasons as they are strong enough to rotate the glasses and can achieve various different rotating speeds. In the case of *Tonality measured by distance*, the slowest speed was selected so that the transition between the tones this movement produced would be as slow as possible.

4. Refractions (2010)

A sound installation

4.1 Concept

Refractions is another kinetic sound installation, and the second piece in a series of works that investigate the relationship between sound and the medium through which it is being transmitted. The aim of this piece is to expand the observations from *Ripples* on the interaction of sound with the medium through which it is being transmitted, and further explore the phenomenon of sonic refraction. As Thomas B. Gabrielson explains in his paper[24], one of the factors that can produce the phenomenon of sonic refraction is the movement of the medium through which an acoustic signal is being transmitted (in this case the medium is air):

> In still air, sound waves travel with a speed that depends on the temperature of the air. If the air is also moving, this motion adds to the wave speed if the wind is in the direction of travel and it subtracts from the wave speed if the wind is in the opposite direction. […] Stokes understood that a wind that increases in speed with altitude would bend wave fronts travelling in the upwind direction, lifting them away from the ground. This would produce a rapid decrease in audibility. In air, the effect can be so strong that a signal heard clearly at some distance downwind may, at the same distance upwind, be faint or inaudible.

[24] *Refraction of sound in the atmosphere*, 2006, Thomas B. Gabrielson, paper published in *Acoustics Today* magazine, April 2006, pp. 7-16

Distant drones such as sounds from flying helicopters, or highways in the distance are ideal for the observation of sonic refraction. On audio CD 3, recording number 4 is the sound of a helicopter passing above my garden. In this recording we can hear the sound of the helicopter fading out in the distance, followed by the sound of the wind the helicopter caused, and we can also observe fluctuations in the amplitude and the frequency of this sound. In addition, we can also observe a downward shift of the overall frequency due to the Doppler effect (00:03 – 00:06). On the same CD, recording number 5 is the sound of a helicopter hovering above a fixed position. We can still hear some subtle fluctuations in the frequency and amplitude of the sound, caused by the reflection of sound on the blades of the revolving helix, as well as the movement of the air underneath the helicopter. These observations drove my interest towards an examination of the relationship of sound with the movement of the medium in which it is being transmitted.

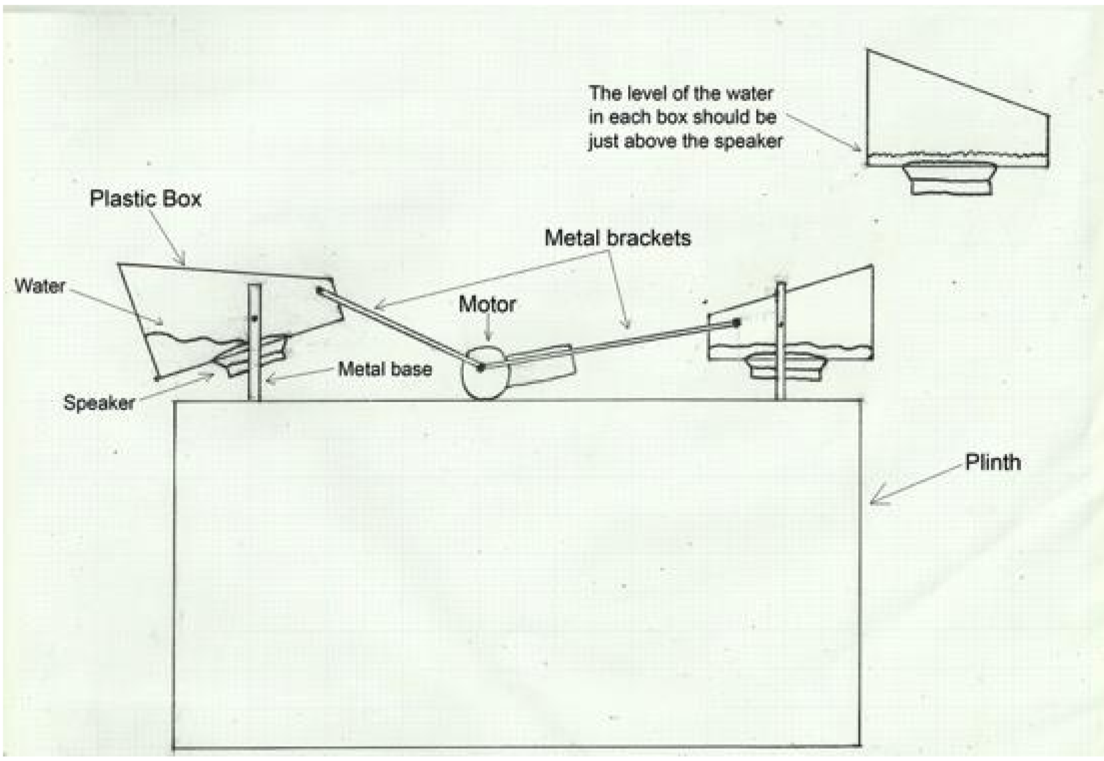

Figure 1: Diagram of *Refractions*

Just like *Ripples*, *Refractions* explores the way sound transforms as it is transmitted through two different mediums, and the way the motion of these mediums shapes the sound. In this case, I constructed trapezium - shaped boxes with a speaker fitted at the bottom (Figure 1). These boxes were filled with water and were attached to a windscreen wiper motor that gently pushed them back and forth. As the boxes rock the speakers submerge and resurface from the water. The speakers are playing a sine tone, and as they dive in and resurface out of the water they cause a very subtle vibrato to the tone. Lights are placed in front of the boxes that project the shadow of the moving water on the wall behind the work. This way the work visualizes the sonic refraction by magnifying the motion of the water, and emphasizes the factor that causes this acoustic phenomenon while also creating an immersive audio – visual environment for the audience.

4.2 Methodology

I investigated different elements that could shape sound, such as the density and movement of the medium, and I started experimenting with the way sound is affected by the density of the medium. During these first experiments I was trying to transmit the same sound through two different mediums simultaneously and observe differences in their frequencies, or phenomena such as “beats” created by the interference between these sounds. Even though these first experiments did not have the expected result, they presented me with another direction the piece could take and were later developed in the sound installation *Observing density through standing waves* (detailed in the following chapter).

For my initial experiments, I chose to use water and oil as the mediums; the reason for this decision is that the densities of water and oil are very different (oil is much lighter than water), and I thought that the effects of the different densities on sound would be more obvious. I was looking for a way to capture the same sound going through those two mediums at the same time, and see if I could observe effects such as “beats” on the sound produced by the effects the different densities of the mediums have on the speed of the sound.

The first system designed for this purposed involved two plastic food containers (Figure 2). One of the containers was filled with water and the other one with oil. Small waterproof speakers were immersed in each of the mediums, at the same spot in each of the containers. A contact microphone was placed on one side of the container in order to capture and record the sound as it moved through the medium and bounced off the walls of the container.

Figure 2: Early experimental set up

The speakers that were immersed in the medium were facing the part of the container directly opposite to the one with the microphone on it. This way the microphone was picking up the reflection of sound in the container. The distance of the speaker from the wall of the container was about three centimeters, and was measured so that each speaker had more or less the same distance from the wall and the contact microphone so that any effect in the quality of sound would mainly be the outcome of the difference in the speed of sound, rather than the outcome of the difference in the distance the sound travels before it reflects on the walls, and before it reaches the microphone.

The sounds that were employed in these experiments were sine tones, because sine tones are elementary sonic elements. Sine tones are pure tones with fixed frequency and amplitude, and they have the ability to produce very clear “beats” with the slightest difference in speed, phase or frequency between them. During the first stages I have also experimented with various different sounds such as field recordings and recorded music. These sounds however did not produce any obvious effects. During these experimentations I started making some sketches with possible ways in which these experiments could evolve to a sound installation (Figures 3 and 4).

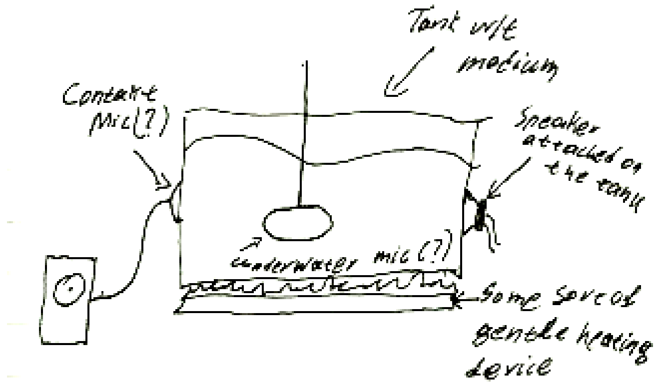

Figure 3: Sketch drawn as a result of the first experiments

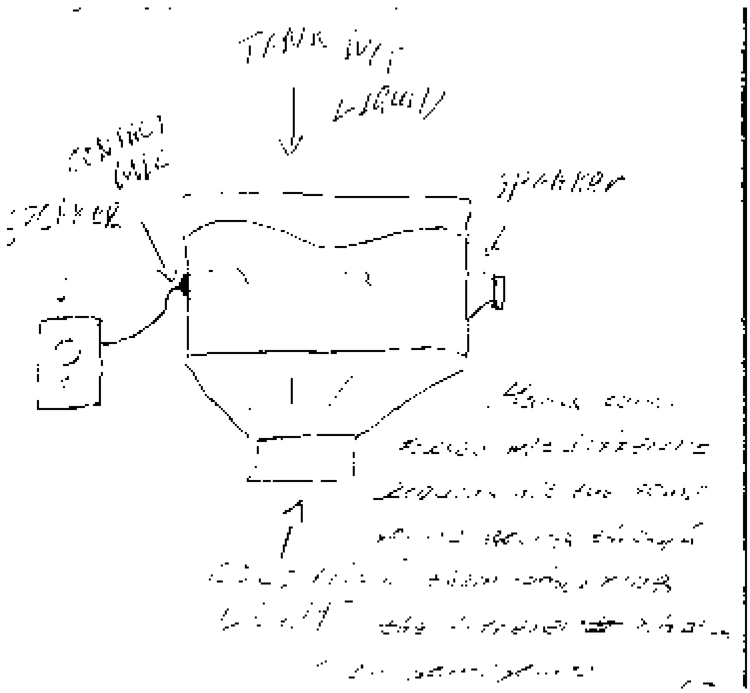

Figure 4: Another early sketch.

These experiments however were not very successful. Even with the sine tones, the effects on the sound were barely noticeable, and capturing the sound through the contact microphone proved to be very problematic. During the course of these experiments however, I observed a very intriguing effect in the quality of the sound every time the medium was agitated. Fluctuations occurred in the frequency and amplitude of the sound coming out of the medium, and produced a subtle “vibrato” effect. I thought that these fluctuations on the frequency and amplitude of the sound had to be related to the movement of the mediums, as Thomas B. Gabrielson also explains in his paper (see 2.1 Concept). In this case, the experiments did not produce the effect that was initially expected but they were very important in the creative process, as they have revealed a new approach to the demonstration of the relationship between sound, and the medium in which it is produced.

Following this observation, I started new experiments with a completely different approach. I constructed a plastic box and fitted a waterproof speaker at the bottom (Figure 5).

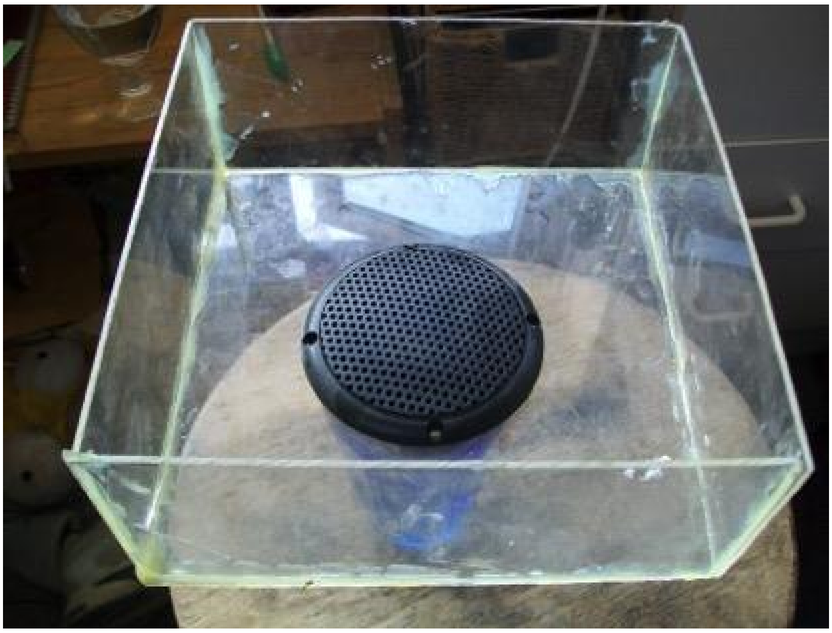

Figure 5: An early prototype of the boxes used in the final work

I filled the box with just enough water to cover the speaker, so that the sound that was coming out of the speaker would be audible as clearly as possible, and started experimenting with different ways in which I could move the medium and produce fluctuations in the frequency and amplitude of the sound. This time I decided not to use oil, as I wanted to focus on the movement of the medium rather than the effects of the difference of the densities of two mediums.

Following the practical experimentations detailed in *Ripples* and the way I moved the glasses back and forth, I developed this idea into square trapezium-shaped vessels made out of Plexiglas, with a speaker fitted at the bottom. The shape of the vessels was trapezium because it allowed the boxes to lean forward without spilling the water. The vessels were fitted on a base, so they could rock forwards and backwards, and were attached with a metal bracket to a motor (Figure 6). I constructed two vessels and used two speakers in order to create an interaction between the phases of two sounds coming out of a moving medium.

Figure 6: Trapezium shaped vessel connected to a motor with a metal bracket.

I filled the boxes with enough water to cover the speaker and placed a flashlight next to the base, so that the reflection of the vessel and the water is projected on the wall behind it (Figure 7). The reason for this decision was that I wanted to visualise the movement of the water inside the boxes through the projection of its shadow on the wall, and visualize the way this movement affected the sound coming out of the speaker.

Figure 7: First realizations of the work

I connected the speaker to my computer through an amplifier, and used a pure wave generator in Logic Pro to generate a sine tone. I then performed slow, upwards and downwards sweeps across the range of audible frequencies (from 20Hz to 20kHz). Through this process I was trying to determine a frequency that would best respond to the movement of the water inside the box.

A sine tone at 347 Hz seemed to have the most distinguishable effects. As the vessel rocked gently I observed very subtle effects during the speaker's submersion and emergence, such as fluctuations in the frequency and amplitude of the tone. When the vessel was at the highest position and the speaker was - for the biggest part - out of the water, the sound was very loud. An overtone was noticeable, due to the fact that the speaker was still covered with water, about one quarter of the way. The sound was partly being transmitted through the air and partly through the water. The movement of the water was changing the way sound reflected on its surface before it propagated in the space and added an extra layer of fluctuations in the frequency of the sound. As the speaker was slowly diving, the loudness of the sound gradually decreased until the sound became very soft and barely audible. The frequency and amplitude of the sound fluctuated gently as the water above was still moving. The movement of the water was portrayed on the wall, and the synchronization of the motion of the gestures of the sound (i.e. vibrato) with the movement of the water became apparent.

At a later stage I installed the work at Oxford Brookes University, originally for some short trials, and then for a short exhibition (Figure 8). During these first trials, one of my aims was to resolve some technical issues related to the construction of the piece. I was looking for a way to keep the motor steady, determine the best positions for the boxes in order for them to move freely, and try to work out some equipment-related issues all of which were later resolved. My main aim however was to determine with certainty the sonic material (refer to section 4.4 Materials) that would best emphasize the effects of sonic refraction in that space, as well as the effects of the motion of the medium in which sound is produced, or reflected.

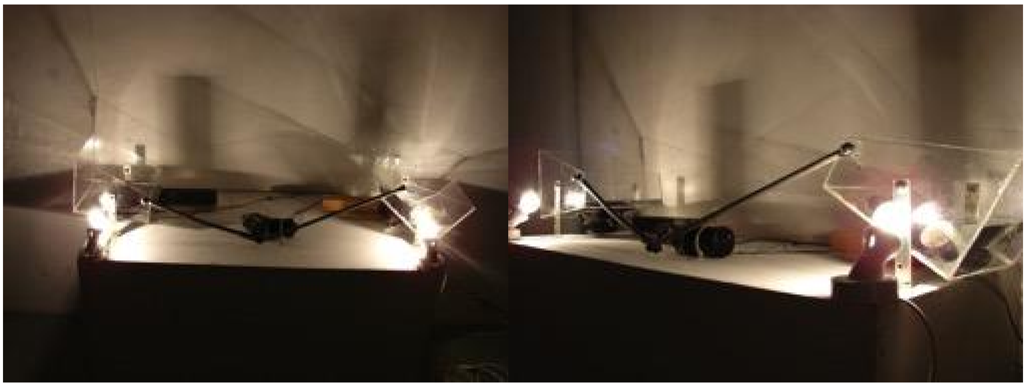

Figure 8: The first trials of the work

After these trials, the work was briefly exhibited for two days in The Arena, at Oxford Brookes University on the 11 and 12 of March 2010 (Figures 9 and 10).

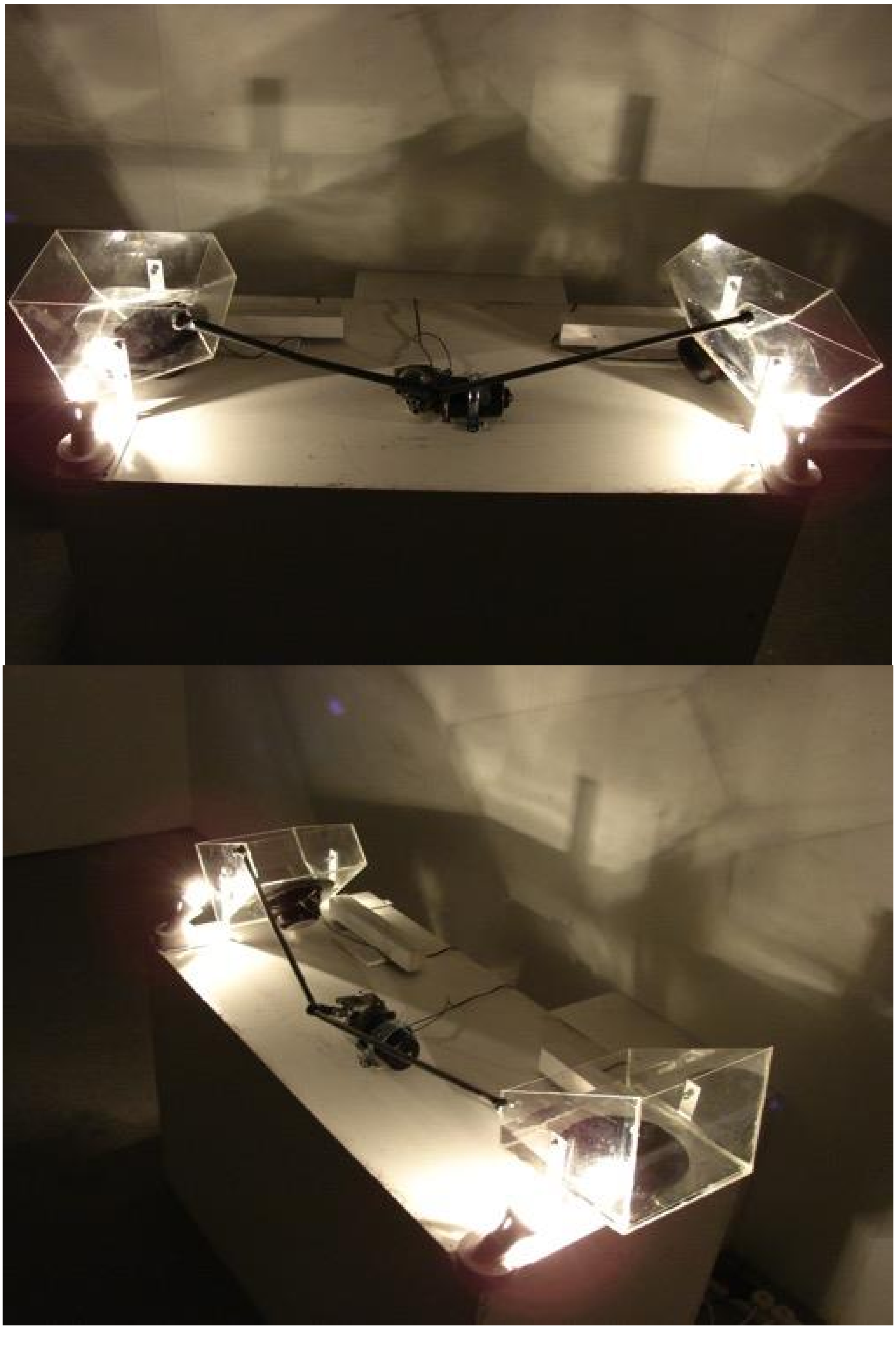

Figure 9: The work in its final form

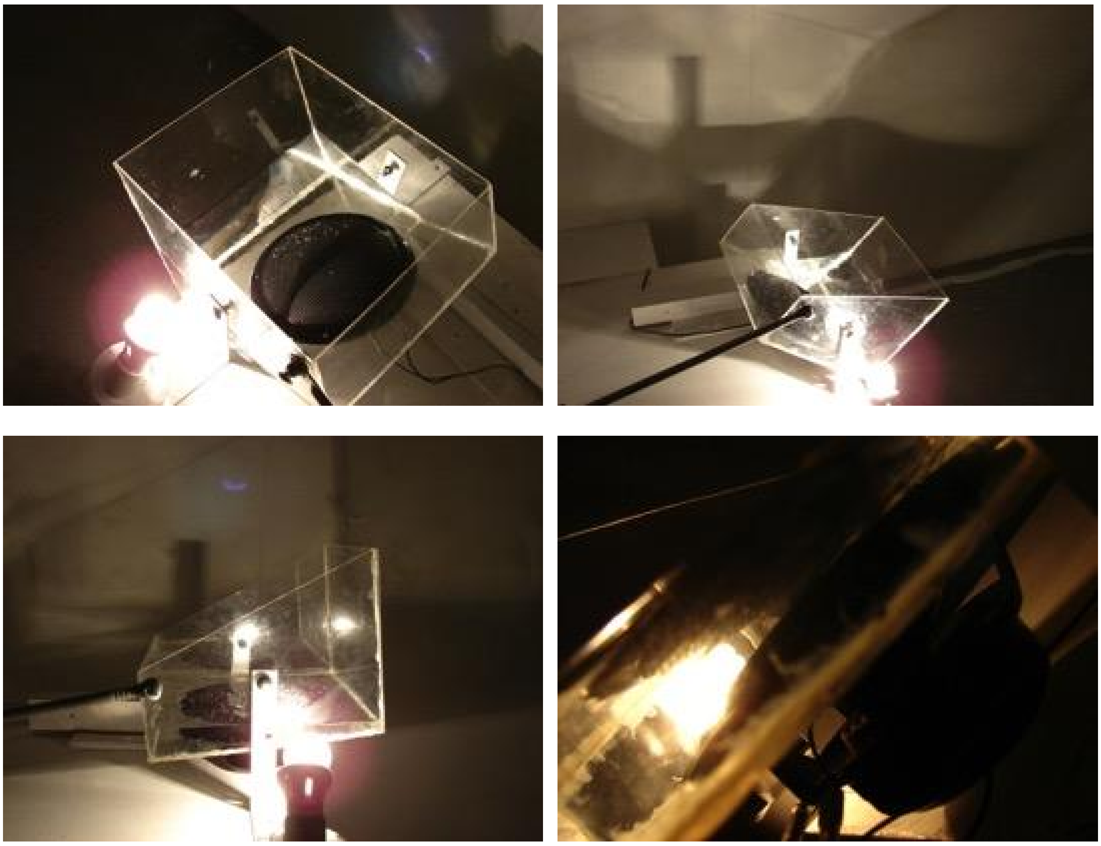

Figure 10: Details from *Refractions*

4.3 Research context

Two works by German composer and sound artist Carsten Nicolai define the research context of *Refractions*. In 2000, Nicolai produced two sound installations that utilize the visualization of sound on water as a material, in different contexts. In his sound installation *Frozen water* (2000), Nicolai uses two glass flasks of different sizes placed in front of a pair of tube – like speakers. The flasks are filled with water half way and the speakers emit a low frequency sound that causes the water in the flasks to vibrate.

Figure 13: Frozen waters
(© Carsten Nicolai)

The wave patterns created on the water by the vibrations of the sound are more intense and chaotic in the smaller flask. In the large flask the patterns are more minimal and scarce. The artist uses this image to demonstrate "a situation that is difficult to control and focuses on the polarity of the elements chaos and order, movement and stagnancy"[25]. In a text[26] found in the catalogue accompanying an exhibition of the work at the Intercommunication Center in Tokyo in 2000 the artist wrote:

> <compressor. snow>
> a thought is a snow crystal
> the nucleus creates a form – intuition and spirit frozen
> points compressed to signs –
> [doubled] split and decompressed into poles –
> an intermediate field becomes the true medium.
> frozen worlds set a tension.
> the gaze never fixes only one part –
> thought loops. the rotation starts
> a moment gains movement – time a sound
> the velocity of rotation encloses the notion of time
> repetition becomes mechanical –
> the mistake crystallizes

[25] http://www.carstennicolai.de/?c=works&w=frozen_water - last accessed 20/09/2012
[26] Carsten Nicolai, 2000, text published in *Sound Art: sound as media* edited by Hatanaka Minoru and Nozaki Takeo, NTD Publishing Co., Ltd., p.27

In 2000 Nicolai produced another work that utilized the same material entitled *atem*. This piece explores the way in which physical vibrations transmit through the floor, and used glass flasks with water to visualize these vibrations. Nine loudspeakers diffusing a bass sine tone were fitted into the wooden floor of a room. Two flasks that were filled with water half way and were placed on the floor. The vibration was transmitted through the floor and created wave patterns on the water.

Figure 14: Atem
(© Carsten Nicolai)

In these two pieces the artist uses water as a means to visualize sound through the wave patterns that are created on the surface of the water as the sound transmits through it. This relationship is used in each of the works as a vehicle to express different ideas and concepts. *Refractions* on the other hand aims at a somewhat reversed version of this relationship. I am exploring the movement of the water and its relationship with sound, and I am using sound in order to amplify and present this relationship. Rather than visualizing sonic movement through water, I am exploring the movement of water through its ability to transform sound.

4.4 Materials

The sonic material for this piece is a computer generated sine – tone, which is recorded on a CD and played back from a CD player. After I explored several other sounds, I chose the sine – tone because of the effects that were produced through its interaction with the moving water. In the visual field, if we want to demonstrate the refraction of light when it passes through water the best material is a laser beam. The laser is one single fixed frequency of light, and is more focused. Because of that fact, the change in the directionality of the laser when it enters the water is very clear. Interestingly, in a sense a sine-tone is the sonic equivalent of a laser beam: it is a single, fixed frequency of sound with steady amplitude. The sine-tone can be very sensitive to effects such as changes in the phase between the two speakers. In *Refractions* there are several factors that lead to these changes in the phase between the two sounds such as the motion of the speakers, but the most important factor is the change in the directionality of the sound occurring due to sonic refraction, and also by the way sound reflects on the surface of the moving water when the speaker is immersed in it half way.

During the trials before the exhibition of the piece at Oxford Brookes I conducted experiments with various frequencies and with slow sweeps of a computer-generated sine-tone covering the whole bandwidth of the audible range. The overtones that were observed in the very first experiments when the speaker was immersed half way in the water was gone, however the "beats" between the sounds from the two different speakers were very clear. After a few trials I chose to use a frequency of 647 Hz - different to the one used during the experimentations - during the exhibition because it produced more distinctive beats in the space in which the work was exhibited.

5. Auditory Rainbows (2010)

An experimental composition
Audio CD1, Tracks 2 & 3

5.1 Concept

Auditory Rainbows is a composition for piano, wineglasses, tie clip microphones and loudspeakers. The wineglasses are attached on microphone stands that hold them above the strings of the piano. The microphones are placed inside the wineglasses, and are connected to loudspeakers that are placed around the piano. Each microphone is connected to a separate speaker, and each speaker is facing the microphone it is connected to. The diagram in Figure 1 shows the inside of a grand piano and the position of the glasses that are suspended above the strings. During the performance, the piano lid is open half way so that the sound reflects back into the body of the piano.

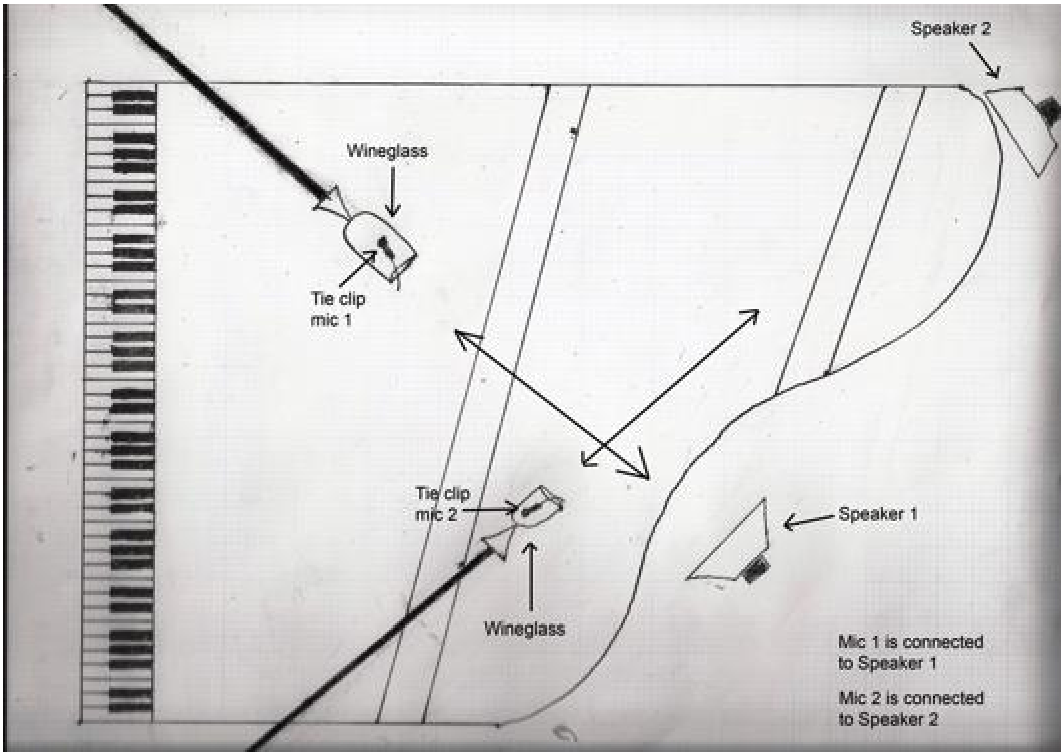

Figure 1: Diagram of the glasses and the microphones inside the piano.

When the volume of the microphones is turned up, two feedback loops are created between each microphone and each speaker. The frequencies of the feedback loops are primarily determined by the size of the glasses, but as will be discussed later they can also be influenced by the size of the space in which the piece is performed. In a big space, if the sustain pedal is held, a low feedback tone gradually builds up. The two glasses used in the recording, as well as the performance, of the piece (the same ones used in *Tonality measured by distance*) resonate at 600Hz and 1000Hz. The performer has to explore methods of creating an interaction with the feedback loops in two ways: by selecting pitches that are capable of producing beats of sonic interference with the feedback loop (the pitches closest to the frequency of the feedback loop), and by playing pitches that are capable of altering the frequency of the feedback loop and produce other interesting effects, such as harmonics. Some examples of these effects can be heard on the recordings (CD1, Tracks 2 and 3), on the following time marks:

<u>Live recording:</u>

00:15 When the first pitch of the piano is hit, a G#, it produces a pulsating beat as the pitch decays.

01:38 When the piano hits a low F, very subtle overtones are produced as the pitch interacts with the low feedback tone.

04:46 When the high cluster chord is hit, the frequency of the feedback shifts upwards momentarily, and quickly returns to its original tone.

06:36 – 06:42 These two chords cause a shift in the frequency of the feedback tone.

Studio recording:

00:14 Same as in the live recording, when the piano hits the G# (the first pitch) a pulsating beat is created by the interference between the pitch and the feedback tone.

00:31 When the piano hits C#, the frequency of the feedback loop shifts upwards momentarily and quickly returns to its original tone.

00:52 The low D# sharp creates very subtle overtones and beats, and causes a shift in the frequency of the feedback tone.

Just like the Helmholtz Resonators that were mentioned in the chapter on *Tonality measured by distance*, the glasses are capable of isolating an individual resonant frequency according to their size. They interact with the soundscape of a space by isolating frequencies from the sonic components of this soundscape. When the glasses are placed inside the body of a grand piano, and as close to its strings as possible, the sonic components the glasses interact with are the sounds of this piano. The central aim of *Auditory Rainbows* is to use this principle in order to isolate and amplify harmonics from the pitches played by the piano.

A paper by Christopher J. Plack on the way our auditory perception works inspired the title *Auditory Rainbows*. In his paper, Plack explains the way in which the basilar membrane of the cochlea (a spiral tube located in the inner ear) is constructed in order to filter an acoustic signal, and separate the frequency components of the sound we are hearing. These frequency components are converted into electrical impulses and are transferred to our brain where they are recomposed into the sound we perceive:

> The basilar membrane at the base of the cochlea (closest to the stapes) is thin and stiff and is most sensitive to high-frequency pure-tone components. The basilar membrane near the tip or apex of the cochlea is thick and loose and is most sensitive to low-frequency components. These properties vary continuously along the length of the membrane so that each place is most sensitive to a particular characteristic frequency. […] The main function of the basilar membrane is to separate out (to a limited extent) the different frequency components in a complex sound. When we hear a sound with high-frequency components, such as a cymbal, the basilar membrane vibrates most strongly near the base. When we hear a sound with low-frequency components, such as a bass drum, the basilar membrane vibrates most strongly near the apex. However, the basilar membrane has much more resolution than this example suggests. In fact, the basilar membrane can separate out the individual harmonics of a complex tone. In a sense, the ear transforms the sound waves entering the ear into a sort of auditory rainbow, just as water droplets (or a prism) separate out the different frequency components in light to give us the visual version. [27]

Glasses of different sizes with microphones inside them create a similar situation: each glass isolates a different frequency component from the pitches played on the piano. The frequency component is then amplified through its continued circulation between the microphone and the speaker,

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[27] Christopher J. Plack, *Auditory Perception,* 2004, Psychology Press Ltd., pp. 5-8

and instigates a feedback loop. The system created with the microphones and the glasses analyses the sound of the piano to its basic frequency components in the same way, and as Plack suggests, in which light is filtered through a prism and analyzed to its basic colour components. This piece creates auditory rainbows in the form of feedback loops.

This composition also exploits the phenomenon of sonic interference. As demonstrated in the examples from the recordings of the piece, when the frequency of the pitches of the piano is close to the frequency of the feedback loop, the interference between them creates pulsating beats and harmonics. In the first example of the live recordings for instance, the base frequency of G# is around 430Hz, and the strongest harmonics of this pitch are all found in the area between 350Hz and 600Hz. The frequency spectrum of this pitch fluctuates very close to the frequency of the glass that resonates at 500 Hz. The proximity of the frequencies of these two sounds creates the pulsating beats[28].

The pitch played by the piano interferes with the feedback loop in the space, and together they create a new sonic event, the pulsating beats. In many instances in the piece (as demonstrated in the examples of the recordings previously), the pitch played by the piano also shapes the frequency of the feedback loop. The feedback loop is created by the pitch of the piano, and then interferes with this pitch to create new sonic events such as beats and harmonics. This process exposes a way in which sounds can multiply through sonic interference, and create new sonic events or auditory illusions.

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[28] Refer to Appendix I: Glossary of Terms, p. 118 for a complete explanation of the phenomenon of sonic interference.

5.2 Methodology

This piece is linked to my previous work, *Tonality measured by distance*. The exploratory process for *Auditory Rainbows* started with the experiments on the interaction of the resonating glasses with external sound sources, mentioned briefly in the methodology (section 3.2) of *Tonality measured by distance*. I started improvising with electronic sounds mixed with the feedback loops created by the resonating glasses, and recorded two versions of the improvisation entitled *A white noise mass* (CD2 Tracks 1 and 2). The software used in these experimentations was Ableton Live, and was employed in order to instigate the feedback loops, and process the rest of the sounds. I set up two glasses with tie clip microphones inside them in front of two speakers (left and right).

Each microphone was connected to the speaker behind it through a laptop that mixed all the sounds together and allowed me to control the volume of the microphones. I was controlling the frequency of the feedback coming out from the speakers in the way described in the methodology section of *Tonality measured by distance*. I was moving my hands closer to, or away from, the glasses and at the same time, I was trying to introduce other sounds into the mix and explore the way they interact with the feedback loops. Some other sounds used are processed noises from various circuit boards, a turntable, a coil used as an electromagnetic microphone and various other noise making objects such as a computer heat sink with a contact microphone attached to it. My aim was to experiment with various sounds with different qualities, such as percussive sounds from the computer heat sink or long noises from the interferences the electromagnetic coil was picking up.

During these experimentations some interesting interactions between the electronic sounds and the feedback loops did occur. For example, in 01:34 of Version 1 (CD2, Track 1) of the recording, the loud noise (a coil used as electromagnetic microphone, passing over the laptop) instigates a feedback loop in a similar frequency, and with a very fast vibrato. In 01:42 of the second version (CD2, Track 2), some of the overtones of the noise are emphasized through its interaction with the feedback loop. I was moving my hands above the glasses upward and downwards, and trying to modulate the frequency of the feedback tone in order to tune it to the frequency of the noises. This way I thought I could maximize the interaction between the feedback tones and the electronic sounds. Except very few moments of obvious interaction between the two sounds like the ones mentioned earlier however, for the biggest part the movement of my hand affected the frequency of the feedback loop more than the sounds coming out from the speakers.

In addition the feedback tones were coming out from the same speakers as the electronic sounds and this made the exploration of the interaction of the electronic sounds with the glass difficult. I thought the best approach would be to use an external sound source, pointed directly towards a resonating glass. The use of an external sound source would reveal whether the glass could be used as a sort of a physical filter between the microphone and the sound source. The sound coming out of the loudspeakers would be the final, or processed, version of the sound from the external sound source, so the effects from the filtering through the glass (if any) would be easy to observe. The sound source should be placed as close to the glass as possible so that the sound would reach the glass instantly, and would not disperse and interfere with other sounds before reaching the glass.

The next sound I decided to try was the sound of my voice. This decision was informed by the research I did on the piece *I am sitting in a room* by Alvin Lucier. I was intrigued by the way in which the voice triggers the resonant frequencies of a space in *I am sitting in a room* and I wanted to explore the way in which my voice would interact with such a small resonating space as a wineglass. For this experiment I used a glass that resonates at 500Hz, as the range of my voice is quite low and I wanted to experiment with a frequency within this range. I placed a tie clip microphone inside the glass that was connected to my speakers. I placed the glass right in the centre of the speakers, and turned the volume of the speakers up.

When the feedback loop started I stood in front of the glass, and as close to it as possible, and started singing long held pitches, and melodies. This time I was not interacting with the glass with my hand as before, but I allowed the frequency of the feedback loop to be shaped just by the sound of my voice. I started by singing a pitch close to the frequency of the feedback loop and then started sliding this pitch upwards and downwards, and trying out several different pitches, listening for interesting effects. A recording of this experimentation (Audio CD 2, Track 6), demonstrates that the interaction of my voice with the feedback loop is very intense: besides beats between the two interfering sounds, my voice was capable of changing the frequency of the feedback loop. After this experiment I realized that an external sound source, placed close to the resonating glasses, could produce very interesting effects and shape the pitch of this feedback loop.

I wanted to expand these experiments, and explore the interaction of the resonating glass with a different sound source. I wanted to try and see if I could replicate the results I observed during the experiments with my voice using the sound of a piano. This idea was informed by a composition by Alvin Lucier entitled *Music for Piano and Slow Sweep Oscillators* (detailed in section 5.4). I started my experimentations with an upright piano. I opened the piano lid in order to gain access to its strings, and placed a glass close to the strings, about 8cm from the hammer mechanism. I placed a tie clip microphone inside the glass, and connected it via a laptop (acting only as a mixer) to a speaker placed on top of the piano (Figure 4).

Figure 4: The position of the glass with the microphone, and the speaker

I turned the volume of the microphone up until a feedback loop of 900Hz was instigated. At first I started experimenting with long held pitches, starting from the pitch of the feedback loop and moving around it. The interaction between the feedback loop and the sound of the piano was not very strong. Besides a few occasional beats between the two sounds (when their frequencies were close), no other effects were observed. The feedback loop remained constant for the biggest part. I tried positioning the glass in different spots across the area in front of the piano strings, and also tried using several different types of glasses, but the results were the same. After several experiments I replaced the cover of the piano, and placed the glass inside the piano, so that the sounds from the piano would resonate inside its body allowing more time for their interaction with the resonating glass.

I started again from the pitch closest to the frequency of the feedback loop, and played around it. Gradually, I started playing all the way across the register of the piano, trying out chords, melodies, and long held pitches. This time the pitches played by the piano were resonating inside its body, and around the glass, creating some very interesting effects such as harmonics and beats. Some of these effects can be heard on a video I made from these experiments entitled *Auditory Rainbows process*, and found on the DVD accompanying this thesis. In the beginning of the video for example (00:06 – 00:10), the first two notes played by the piano, an A followed by an A#, create two distinct beats through their interaction with the feedback loops. Later, at 00:14, the harmonics of the two pitches played by the piano (F# and G#) are amplified and create an interesting texture. After these experimentations I realized that the best set up was with the cover of the piano strings closed and the glass inside it, so that the sound would reflect and amplify inside the piano producing stronger overtones, which would reach the resonant space of the glass instantly.

In order to develop this principle I repeated the experiments with a grand piano that allowed me to use more glasses, as it was bigger than the upright piano. I attached the glasses with the microphones inside them on microphone stands so that I could suspend them above the strings of the piano, inside the body. I started my experiments with three resonating glasses, the same number I used in the first exhibition of *Tonality measured by distance*. I wanted to create a situation in which three distinct feedback loops would be instigated, and the sound of the piano and these feedback loops would be interweaving seamlessly as in the video of the experiments with the single glass. The three glasses however resulted in a single, very loud feedback loop that was overshadowing the sound of the piano. The microphones in the three resonating glasses were picking up the feedback loops from all three speakers being used, and created a single very loud feedback loop.

I decided to reduce the amount of the resonating glasses to two. This seemed to work better as the two feedback loops were clearly distinct (600Hz and 1000Hz), and easier to control because they did not interact with each other much and did not result in the single, loud tone mentioned earlier. After trying several positions between the glasses and the speakers I decided that the best set up is the one depicted in Figure 1. I connected the microphones to the speakers via Logic Pro on my laptop so that I could control their volumes simultaneously. I turned the volume of the resonators up, and started to improvise with the feedback loop that was created. During the improvisation I followed an approach similar to the one mentioned earlier. I started by determining the tonality of the feedback loops by finding the closest pitches on the piano, and gradually moved away from them covering the full register of the piano.

My aim was to determine the notes that had the strongest interaction with the feedback loops (and were able to alter their frequency), and to work out the dynamic range of the piece. I was observing the alterations of the beats when I was playing single pitches, and the layering of the beats when I was playing chords. I started playing around with the pitches that produced the most intriguing effects, either forming chords or playing them individually. I repeated each individual pitch, as well as each chord, several times in different dynamics in order to determine the best dynamic range. Higher pitches generally worked best at a higher dynamic range (*mf* to *ff*), as their decay time was shorter. Lower pitches worked best in a lower dynamic range (*p* to *mf*) as when played loudly they could cut out the feedback loops.

However, as the built up of the feedback loops was different with each pitch the dynamic range would be determined from the interaction between the pitches and the feedback loops during each performance. During these experiments, I kept the sustain pedal on the piano pressed at all times because I wanted the pitches to have the longest decay possible. This strategy worked very well in this small space (a room of about three meters wide and four meters long), as it prolonged the interaction between the pitches and the feedback loops.

This was not the case during the rehearsals and performance of the piece in Holywell Music Room: the Holywell Music Room is an Eighteenth Century concert hall, and a very big and reverberant space. Keeping the sustain pedal pressed and allowing the strings of the piano to resonate for a longer period of time resulted in the built up of a very low feedback loop. This happened because the continued resonance of the piano strings would eventually trigger the resonant frequency of the performance space, which was amplified through the microphones and the speakers. This low feedback loop would instantly disappear as soon as the sustain pedal was released. This event however provided the piece with yet another way of creating and controlling one more feedback loop, leading to a more varied and interesting texture during the live performance.

After my observations during the experiments in the small space at Oxford Brookes University, I started thinking about the way that the sonic material of the piano would be organized. I did not want the notes to form melodic material, but rather to explore the physical phenomenon of sonic interference produced by the interaction of the feedback loop with the notes of the piano. A re-evaluation of these observations led to the determination of the overall structure of the piece.

5.3 Structure

Score

Auditory Rainbows
For piano and resonating glasses

Equipment
Glasses, microphones, loudspeaker, mixer

Set-up and introductory remarks

Put tie – clip microphones inside glasses of your choice, and place them inside a piano as close to the strings as possible, but without touching them. Connect each microphone to an individual loudspeaker.

The number of glasses and loudspeakers is entirely up to you, but you should be able to turn the volume of the microphones up or down simultaneously. It is also recommended that you use a limiter in your set-up.

The loudspeakers should be placed around the piano and each speaker should face towards the open part of the glass it is connected to.

Adjust the volume so that the level of the feedback is in balance with the sound of the piano, and an individual distinct tone is heard from each speaker.

The piece is an exploration through which the performer has to determine the notes closest to the frequency of the feedback loop created by the microphones in the glasses.

Through this process, the performer will also discover notes that are capable of shaping the tone of the feedback loop. The goal is to produce beats of sonic interference between the notes of the piano and the feedback loop.

The duration of each note/chord will be determined by the intensity of the beat it will produce. The more intense the beat is, the more the note/chord should be held and emphasized. Think of time in relation to the wavelength of each sonic element.

Play the notes and chords individually without trying to create melodic or rhythmic lines and progressions.

The use of the sustain pedal is up to the performer: determine an appropriate decay time according to the intensity of the phenomenon (i.e. beat) being created.

The piece is divided into three parts and the overall duration is up to the performer. All the parts have to be of equal duration (the performer should use a stopwatch).

Instructions

Part 1

- Slowly turn the volume of the microphones in the glasses up, until the feedback loop starts.
- Play individual notes and determine the central pitches of the feedback, work out the notes that influence the feedback, and produce interesting beats.
- Improvise around these notes and play them individually to produce different beats.

Part 2

- Use the notes discovered above to form chromatic, non-diatonic, chords.
- Each chord must have at least three notes.
- Try to produce more complex textures and beats.

Part 3

- Now play pairs of the above notes.
- Slowly release the tension between the feedback and the notes.
- Hold down the last pair of notes until they decay and slowly turn the volume of the resonators down.

The piece as a whole is an exploration, during which the performer first has to determine the appropriate sonic material, and explore it in different ways and combinations. While listening back to a recording I made from one of the improvisations, I decided to divide the piece into three parts, each part being a different step in the exploratory process of the interaction of the piano with the resonating glasses. In the first part, the performer has to determine the pitches that create the strongest interaction with the feedback loops by playing them individually and trying to create beats, or shape the frequency of the feedback loops. In order to achieve this, the performer first has to establish the tonality of the feedback loops, and start moving away from it.

The strongest beats are created within a range of about three semitones upwards and downwards from each pitch that corresponds to the frequency of the feedback loops. The beats are replicated in every octave in different intensities. The first part is based entirely on individual notes, whose duration is determined by the intensity and duration of the beats that they produce. The decision of the attack (dynamics) is left with the performer. As mentioned earlier different dynamic ranges will produce different effects for some pitches, and the overall range of dynamics is also determined by the loudness of the feedback loops.

During this process the performer will discover the pitches of the feedback loops (as well as the pitches with the strongest interaction with the feedback loops) and improvise around them. In the second part, the performer uses these pitches to form chromatic and not diatonic chords, and tries to produce more complex beats. The performer should not use diatonic chords so that he or she avoids playing chord changes over a tonal center, and focuses on the interaction of the sounds from the piano with the feedback loops. The amount of pitches in each chord is up to the performer, but he or she has to use more than two pitches for each chord in this section. Again, the duration of each chord depends on the intensity and duration of its interaction with the feedback loops. In the third part the performer plays pairs of the aforementioned pitches, slowly resolving the tension between the feedback and the notes. The piece is brought to an end by slowly fading the feedback tones out on the master volume control on the mixing equipment being used, and holding the last pair of notes until they decay.

The overall duration of the piece is open: different resonating glasses can be used for each performance of the piece, and create different interactions. In addition, the system with the resonating glasses will respond differently to the space in which the piece is performed. The performer is free to explore these interactions for as long as he likes, the only rule is that the parts have to be equal lengths. The score is a text with a few simple instructions on the set up and the exploratory process. I did not want to make a score with pre-determined notes and rhythmic patterns because as mentioned earlier the piece can be performed with different glasses each time, which will interact with different pitches from the piano.

The piece will also produce different effects according to the space in which it is performed. As discussed previously, when I performed the piece at the Holywell Music Room in Oxford (CD1, Track 2), which is a big and reverberant space, the feedback loop from the glasses gradually built up to a very low tone. On the other hand, while rehearsing the piece in a relatively small space at Oxford Brookes University (CD1, Track 3) this low tone was not present: the piece produces different soundscapes according to the space in which it is performed. Therefore the sonic material of the piano could not be pre-determined. It seemed appropriate to only give some general instructions on determining, organizing and using the sonic material of the piano, as well as the overall structure and duration of the piece.

5.4 Research Context

An important research context for this composition is *Music for Piano with Slow Sweep Pure Wave Oscillators* (1992) by Alvin Lucier. In this piece, Lucier explores sonic interference and the production of beats between a sine tone, and pitches played on a piano. He uses a pure wave oscillator, whose frequency moves slowly upwards and downwards. The performer has to play notes on the piano that correspond to the frequency of the tone and try to produce beats through the interference between the tone and the notes of the piano.

As the frequency of the tone moves up and down in slow sweeps, the performer is playing different individual pitches and chords following the sweeps of the tone. This creates a multi – layered texture; one layer is the sine tone, which drives the overall tonality of the piece. The second layer is made from the notes from the piano that create a texture with their long decays, and the third layer is made from the beats created by the interference of the notes with the tone. In this case however, the performer cannot control the frequency of the oscillator and has to follow the tone as it sweeps up and down.

Auditory Rainbows extends this idea, and develops a system in which the notes the performer is playing will shape the frequency of the interfering feedback loop, which in turn will shape the note of the piano. This creates an interweaving relationship between the two sonic elements. Besides sonic interference, *Auditory Rainbows* aims at the creation of an effect similar to a rainbow, by using different vessels that can isolate resonant frequencies from the notes of the piano in a similar way a prism would analyse light to its basic colour components.

The resulting texture in *Auditory Rainbows* is different to that of *Music for Piano with Slow Sweep Pure Wave Oscillators* as well. In *Auditory Rainbows* two tones are created through the use of two glasses of different size. Instead of remaining fixed throughout the piece the frequencies of the tones shift abruptly when the performer plays a note capable of shaping these frequencies, and create short trills between two tones. This adds another layer of interference between the two sonic elements. Furthermore, as discussed earlier, the texture of *Auditory Rainbows* relies heavily on the size of the space in which it is performed. Due to the position of the speakers outside the piano, the resonant frequency of the space can be amplified and added to the performance of the piece, as the recordings from the studio and live versions demonstrate.

6. Observing density through standing waves (2011)

A sound installation

6.1 Concept

This piece builds upon previous experiments on the interaction of sound with the medium it is being transmitted in. More specifically this project stems from the experiments detailed in the chapter on *Refractions*, in the *Methodology* section (4.2). In addition, this work utilizes methods and materials explored in previous works such as the combination of vessels, speakers, and microphones in order to instigate and manipulate sonic feedback.

Sound is a vibration that transmits through the molecules of the medium in which it is being produced. When these molecules are close to each other (in a dense medium) the vibration transmits through them faster, making sound move faster. The elasticity of the medium on the other hand can determine the pitch of a sound: when the sound transmits through a dense medium that is not so elastic the rate of the vibration will be slower and will therefore produce lower pitches. For example, the base frequency of a sound will be lower if it transmits through shampoo rather than water because shampoo is generally denser than water.

The central aim of this sound installation is to demonstrate the way in which the pitch of a sound can be modulated by the density and elasticity of the medium in which this sound is produced. The work exploits the natural behavior of sound in order to ‘listen’ to the molecular structure of different mediums, and observe the way their densities shape the pitch of the sound. This exposes the interconnectedness between sound and matter, and the way in which the density of sound can be determined by the density of the medium in which it is produced.

As mentioned above, the base frequency of a sound can be modulated by the elasticity of the medium in which it is being transmitted. Low frequency sounds have longer wavelengths than high frequency sounds, and therefore affect a bigger mass of the medium in which they are transmitted. A good example of this is the sound of very loud dance music in a night club, where the loudness of the sounds of the kick drum and bass, in combination with their wavelengths, can move such a big mass of air that can literally make the physical space shake (usually this effect is not perceptible with other sounds of higher frequencies, such as keyboards or snare drums). On this instance, sound becomes more tangible and we can feel its presence in the space physically. The relationship between sound and the medium in which it is produced reveals an analogy between the material manifestation of sound and the density of the physical medium in which this sound is transmitted.

In order to explore this analogy, this work utilizes four tubes, each filled with a medium of different density: air, sunflower oil, water and shampoo (Figure 2). These mediums were chosen because the difference in their densities is manifested empirically: if we pour shampoo in water, the shampoo usually sinks at the bottom before it dissolves completely. Shampoo is therefore denser than water. If we pour oil in water on the other hand, the oil stays on top. This demonstrates that oil is thinner than both shampoo and water, and that these three mediums have different densities. Tie-clip (also known as *lavalier*) microphones are fitted at the bottom of each tube and are connected to a speaker at the top of the tube in order to instigate a feedback loop and create a standing wave inside the tube. The pitch of this standing wave depends on the density and elasticity of the medium.

6.2 Methodology

This sound installation arose mainly out of a process of reflection upon the research that was carried out during this study. The knowledge on the behaviour of sonic feedback acquired through previous works such as *Tonality measured by Distance* and *Auditory Rainbows* acted as a catalyst in the process of re-thinking the early experiments detailed in the chapter about *Refractions*, and presented new ways of realizing a piece that explored the movement of sound through mediums of different densities simultaneously.

Rethinking on my previous work, *Tonality measured by Distance*, I was intrigued by the way in which sonic feedback can clearly present information regarding the behaviour of sound. The pitch of this feedback can be modulated by many different elements, such as the size of the space where it is being produced or other sounds that might interfere with it. I was also reflecting back on the early experiments with different mediums and I have started thinking of ways in which I could produce sonic feedback in mediums of different densities simultaneously, in order to explore the way in which the density of the medium in which a sound is being transmitted can shape the form of the sound.

I started to see a way in which I could produce sonic feedback using tubes filled with mediums of different densities, in order to observe the effects of the density of the medium on the sound that is produced in it. I started making some sketches of how the work might look like. The tubes were hanging from the ceiling, with microphones on the topside, and waterproof speakers at the bottom. (see Figure 1)

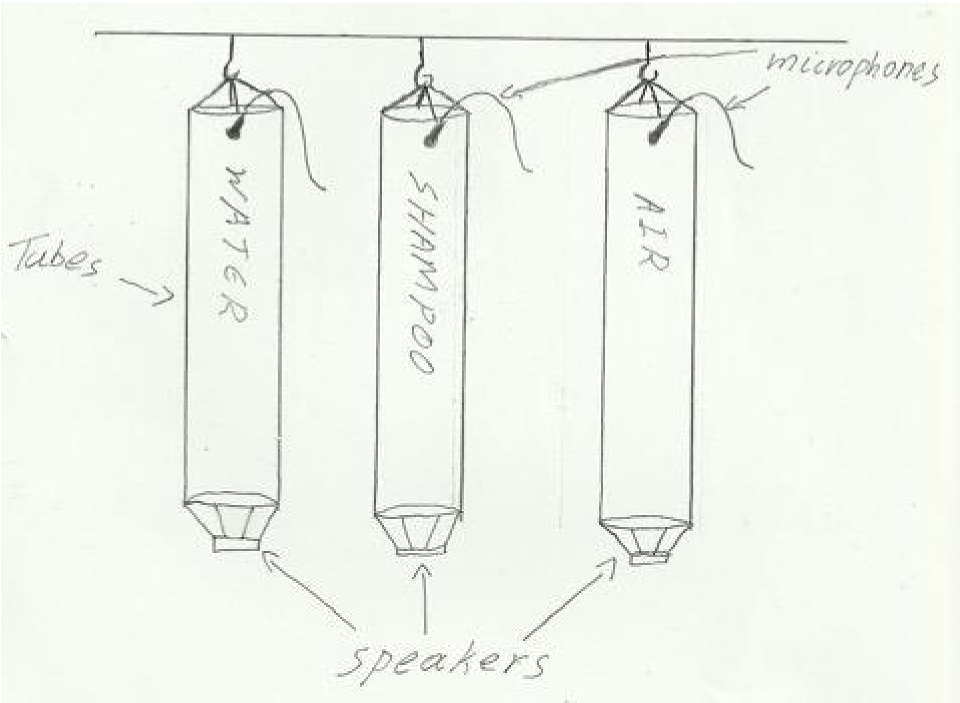

Figure 1: An early sketch of *Observing Density through Standing Waves*

However, I decided to place the speakers on top of the tubes and outside the mediums so that the sound would be loud and clear. I thought of making a base at the bottom of the tube, pass a tie-clip microphone through it, and place the speaker on top of the tube. I decided of placing the tubes on plinths rather than hanging them from the ceiling, so I made some designs of what the work could look like. (see Figure 2)

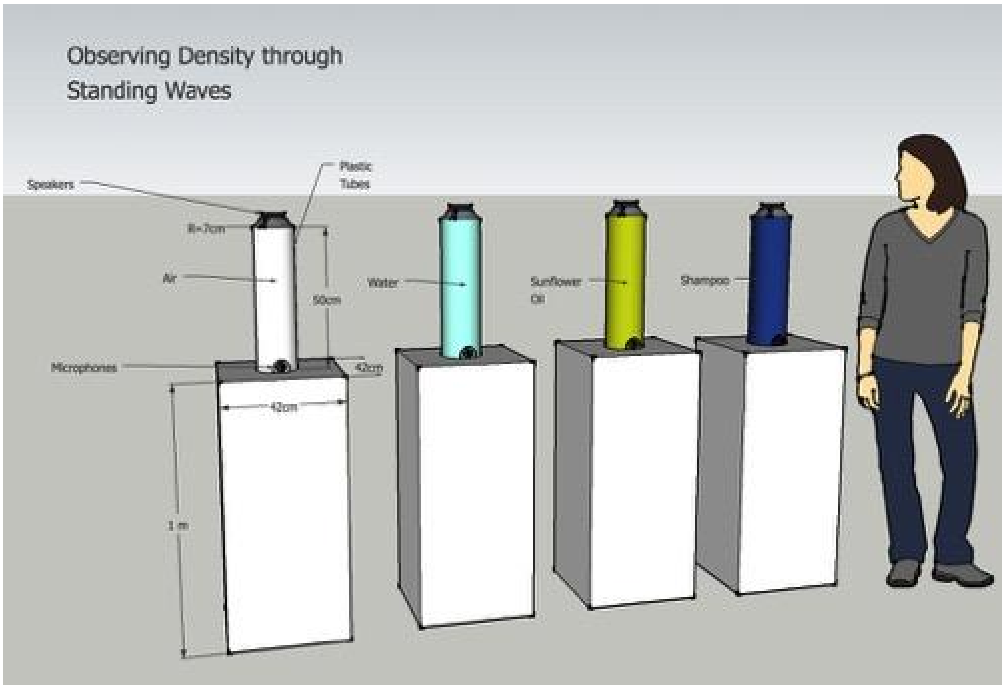

Figure 2: A 3D model of the work

While constructing the piece and working on all the technical aspects, I was exploring ways in which the piece could be presented. I was thinking for example whether the lights in the space would be on or off, or the way I would arrange the tubes in the space. While working on the tubes, I observed the way light passed through them. The light entered from one end, and emerged from the other end as a concentrated beam while lighting the whole tube. After observing this captivating effect I decided to make a big hole on the plinths underneath the tubes, and place strong spotlights inside the plinths so that the tubes would be lit from the bottom. The question regarding the arrangement of the tubes in the space was resolved once I went into the space where the work was first exhibited, at Audiograft 2011 in Oxford from the 14 to the 19 of February 2011. Due to the size of the space I had to place the tubes around the space, two on each side (Figure 3).

Figure 3: The work in its final form, at Audiograft 2011

Air

Sunflower Oil

Shampoo

Water

Figure 5: The mediums at Audiograft 2011

The tubes were arranged around the space according to the density of their mediums, so that the lowest pitches would be on one side (the tubes with the shampoo and oil) and the highest on the other (the tubes with the water and the air). The title of this sound installation is informed by the work of Sato Minoru and it was partly selected as recognition of his influence in this piece. The most important reason for the selection of this specific title however was that it conveyed the purpose of the work to the audience in a very clear way. The title revealed the correlation of the sine tones with each of the mediums in which these sine tones were being transmitted.

The soundscape was a chord composed by four distinct sine tones and was constantly shifting over long periods of time. The resonant frequency of the tube with the shampoo was roughly 160 Hz making it the lowest tone, as the shampoo was the densest of the mediums. The tube with the water was resonating at about 240 Hz, making water the second densest medium. Following these was the tube with the sunflower oil resonating at 250 Hz, and the tube with the air resonating near 486 Hz. The tubes were also interacting with each other, as their microphones would pick up each other's sound as well, causing the frequency of each standing wave to slightly shift upwards and downwards. This interaction was allowed to happen as it added another layer to the soundscape. Furthermore, the chord was changing over long periods of time. This was due to the lights gradually raising the temperature of the mediums in the tubes, making them thinner[29]. As a result, the frequencies of the sine tones were gradually shifting upwards.

[29] When a medium is heated it becomes thinner. A good example is the hot air balloon: the hot air inside the balloon is thinner than the cold air surrounding the balloon, allowing the balloon to fly.

The movement of the audience in the space, and the change of their position in relation to the sound sources also affected their perception of the frequency of each of the tones. The human echolocation system has the ability to filter frequencies according to the directionality of the sound. The outer ear, the pinnae, is shaped in such a way so that it filters the frequencies according to the direction they are coming from, and the way these frequencies reflect on the pinnae. This happens so that our brain can distinguish a sound that is coming directly in front of us from a sound that is coming from directly behind us, as the interaural level differences[30] between these two sounds are the same and do not provide a clue to the direction of the sound.

As the audience moved and changed their position in relation to the direction of the source of the sound, the perceived frequency of the sound shifted. All these shifts and differences in the frequencies of each of the tubes resulted in ever-changing combinations of different “beats” between the tones. This piece was also exhibited at the Global Composition 2012; an international conference on sound, media and the environment held in Darmstadt, Germany from the 25 to the 28 July 2012. The venue was the Hoschüle Darmstadt Media Campus in Dieburg, and the keynote speakers included Prof. R. Murray Schaefer, Hildegard Westerkamp and Bernie Krause.

[30] In his paper on auditory perception, Christopher J. Plack (refer to the concept section 5.1 on *Auditory Rainbows* p. 76) explains that one way that we know which direction a sound is coming from is from the difference in the level of the sound that reaches each of our ears. If a sound is coming from the right for example, it will be perceived as louder from the right ear, and softer from the left ear. The difference between the levels each ear perceives is the interaural level difference.

Figure 6: Detail of the work at the Global Composition 2012
(Photo: Katharina Schmidt)

Air

Sunflower Oil

Shampoo

Figure 7: The mediums at the Global Composition 2012

6.3 Research context

An important research context for this piece is one of the latest pieces by Sato Minoru entitled *Observation of thermal states through a stationary wave* exhibited at The Crypt, in Kortrijk, Belgium[31]. Minoru used four glass tubes, two of which where placed under constant lights so that the temperature in the space inside them was higher than the temperature in the other two tubes. He placed microphones on one end of the tubes and speakers on the other, emphasizing the resonant frequency that was being transmitted through the tubes, and observing the effect the difference in the thermal states had on this resonant frequency. The resulting sound was a pulsating sine tone that was the result of the interference between the resonant frequencies of the warm and the cold tubes.

Figure 8: *Observation of thermal states through stationary waves* (© Minoru Sato)

In this piece, Minoru essentially explores the way the density of the medium affects sound. The air in the tubes that are placed under the lights is thinner, because the tubes are warmer.

[31] Happy New Ears festival from the 13 to the 28 of September 2008

This piece has presented me with a way of using tubes with microphones and speakers in order to demonstrate the effects of different densities. *Observation of Thermal States through a Stationary Wave* however explores the way temperature can shape sound - mostly through the effect temperature has on the density of the medium in which the sound is transmitted. *Observing density through standing waves* on the other hand focuses on the interaction of sound with the density of the medium in which it is produced, and explores four different densities. This produces a more complex soundscape that comprises of four different tones.

6.4 Materials

In order to realize this work I used acrylic tubes. I already had some small speakers, so I knew that the diameter of the tubes should be seven centimeters. Initially I thought that the tubes could be fifty centimeters long but when they were delivered I thought that they could be a bit shorter so that they would look more symmetrical and I cut them down to thirty centimeters. The most important aspect was that they were all the same size, so that the only element affecting the feedback would be the density of the mediums contained in the tubes[32].

At the next stage, I needed to construct a base for the tubes that would also include a system for the protection of the microphones from the liquids. For the base I used pieces of acrylic glass, cut in circles so that they would be in symmetry with the tubes. The system for the protection of the microphone

[32] As it was demonstrated in the chapter on *Tonality measured by Distance* (Chapter 3), the size of the space that contains the sonic feedback shapes the pitch of the resulting tone. If all of the tubes are the same size, the only remaining element capable of shaping the pitch of the feedback is the density of the medium.

was very simple: the microphone was put in a condom and sealed with silicone.

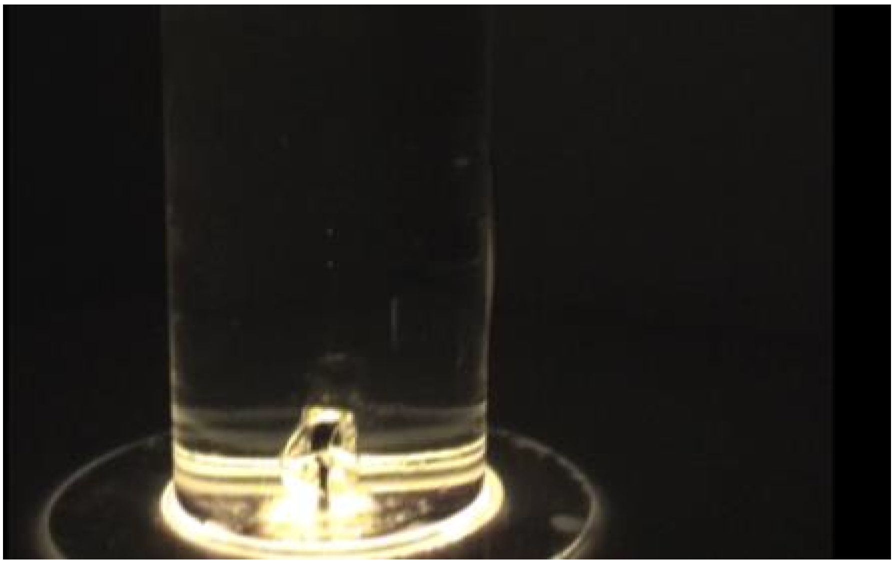

Figure 9: Detail from the base of the tube containing the sunflower oil.

Another way of realizing this work would be the use of waterproof microphones, commonly known as *Hydrophones*. These microphones however were too big and heavy for the tubes to hold.

7. Conclusions

This research project introduces a conceptual approach to sound as a medium that is always subjected to an evolutionary process through interaction with elements from the environment in which the sound is being transmitted. In order to explore this concept, the project defines the territory of “evolutionary sonology”: a practice of experimental sound making that revolves around different fields of sound practice, and presents specific elements from the physical space that can interfere with the evolution of a sound. The interaction of these elements with the evolution of the sound is disseminated to an audience in the form of sound installations and compositions. This interaction reveals the intimate relationships and analogies that are created between the material and the energetic space, as these relationships manifest through aural evolutions.

In dealing with such an approach, the project contributes methodologies, processes, and conceptual frameworks that can be applied in order to approach sound as an evolutionary process through artistic practice. Through these processes, this study also contributes a portfolio of new work that focuses specifically on the evolutionary processes of sound, and engages an audience in the experience of these mechanisms (in most cases while they are operating in real time). The project looks at specific works by other artists that are concerned with the representation, and the use, of science, technology, and natural phenomena. Aspects from the compositional method in each of the works relevant to this project were extended in order to create new ways for the representation of the evolution of sound. This section of the thesis revisits the aims and the questions of this research project, and is a recapitulation of how these aims and questions were addressed through specific examples from the works and their associated creative processes.

Aim 1:

- To explore the way in which sound changes and evolves between the sound source and the listener.

In his essay *About 2 Works* published in *Site of Sound: of Architecture and the Ear*, Toshiya Tsunoda refers extensively to the environmental elements that shape a sound that is being perceived within that environment, and mentions that 'vibration phenomena are shaped by the conditions of the space through which they are being transmitted'[33]. Some of the work by Toshiya Tsunoda focuses on the presentation of an acoustic phenomenon to an audience. In his work *Standardisation of a Standing Wave by a Sine Wave* for example, Tsunoda amplifies the phenomenon of sonic interference and presents it to an audience in the form of a site – specific sound installation at the foyer of the XEBEC Hall.

As Brandon LaBelle also suggests in *Background Noise: Perspectives on Sound Art*[34], the work of Tsunoda focuses on the amplification of otherwise imperceptible acoustic phenomena. Sato Minoru moves along similar lines, and in his essay in *Sound Art – sound as media*[35] he explains that his

[33] Toshiya Tsunoda, 1999, *About 2 works*, published in *Site of Sound: of Architecture and the Ear*, Errant Bodies Press – Smart Art Press, p. 146
[34] Brandon LaBelle, 2006, *Background Noise: Perspectives on Sound Art*, The Continuum International Publishing Group Ltd. p. 238
[35] Sato Minoru, 1999, *Sound Art – Sound as Media,* edited by Hatanaka Minoru and Nozaki Takeo, NTT Publishing Co. Ltd., p.34

interests focus on ‘physical phenomena and their reception’ and defines a more general research territory.

Both Tsunoda and Minoru focus on the amplification of acoustic phenomena and the presentation of these phenomena to an audience in various conceptual frameworks. This approach is a continuation of the work of Alvin Lucier, in the sense that it focuses on the amplification of acoustic phenomena. As Pauline Oliveros describes, Lucier was ‘interested in the phenomenology of sound and the revelation of its natural characteristics and processes as music – making’[36].

The present research project has expanded upon this approach by examining what these phenomena reveal about the evolution of a sound in physical space. This project has focused the approaches of the aforementioned artists in addressing the evolution of sound, and the sonic transformation that occurs through various environmental elements. The creative processes and methodologies that were followed in this study resulted in the creation of original works that present specific aspects of the evolution of a sound. Each of the works focuses on an aspect of a phenomenon that relates to the evolution of sound, and presents this aspect to an audience.

- *Ripples*

Ripples is an electroacoustic composition that was developed from the observation of an evolutionary process of a sound through music technology. Technology was used in order to present this observation to an audience: a

[36] Pauline Oliveros, *Poet of Electronic Music*, introduction to *Alvin Lucier: Reflections,* Musik Texte, 1995, p.12

familiar sonic event that demonstrates an aural evolution is isolated (the sound of the clinking glasses), and the elements of the sound that are affected during its transmission through a moving medium are magnified with the use of electroacoustic techniques such as time stretching and repetition (delay). The structure of *Ripples* is determined so that it first presents the audience with a complex harmonic texture created by the magnification of the sound of the clinking glasses through time – stretching, in order to emphasize the fluctuations in the frequency spectrum of a sound that can be caused by sonic refraction. After the introduction of the magnified sounds, the original sonic material is uncovered in order to reveal the source of this complex harmonic texture to the audience.

- *Tonality measured by distance*

Tonality measured by distance is a sound installation that presents natural resonant frequencies in closed spaces, and utilizes a system that can alter the size of these spaces dynamically in order to change their resonant frequencies in real time. In doing so, the piece engages the audience in an exploration of the way in which the size of the space is related to the evolutionary process of the resonant frequency that exists in this space. This piece presents the evolutionary process of a sound in a space, through a combination of aural and visual elements: it is a visual representation of the size of a space being changed dynamically, linked to an aural representation of the way the alterations in the size of this space shape its resonant frequencies.

- *Refractions*

Refractions is a sound installation created by a system that instigates the interaction of a sound with a moving medium. This piece extends the exploration that began with *Ripples* on the effects of the element of sonic refraction on the evolution of a sound, and creates an audio-visual representation of this element. Just like the previous work, *Tonality measured by distance*, *Refractions* engages the audience in an audio-visual experience of sonic refraction, occurring in real time: the element of sonic refraction is audible in the sound, and the movement of the medium which causes it is presented visually on the wall through the projection of the shadow of this medium.

- *Auditory Rainbows*

Auditory Rainbows is a composition for piano, and resonating glasses that are able to isolate an individual frequency component from the pitches played on the piano. This piece creates a system that interferes with a sonic evolution, and subjects a sound to the same process light is subjected when it passes through a prism: the glasses analyze this sound to its frequency components and amplify a different frequency component according to their size. This possible aural evolution of a sound being transmitted through closed spaces simultaneously is presented to the audience through the "auditory colours" that are created by the interference between the original sound (the pitches played on the piano) and the resulting resonant frequency (the feedback tone). These auditory colours are the beats of different intensities, and the amplified overtones that result from this interference.

- *Observing density through standing waves*

Observing density through standing waves is a sound installation that creates feedback loops in four mediums of different density. The density of the medium through which this feedback loop is being transmitted determines the frequency of each feedback loop. The denser the medium is, the lower the pitch of the resulting tone will be. This way, the audience engages in an exploration of the co-relation between frequency and density, and the effects of this co-relation on the evolution of a sound.

<u>Question:</u>

- How do we perceive the evolutionary process of a sound, from the moment it is produced and until it enters our perception?

During this research project I established a method for the observation of the evolutionary process of a sound. This method relies on the discovery and observation of the same sound in a different situation, and began with my observations of the sound of a metal pot, while I was washing it. When the pot was hit and the water inside it was agitated, I perceived fluctuations in the frequency and dynamics of the metallic sound of the pot.

I re-created this phenomenon through the use of glasses that were filled with water, and were being hit with a drumstick while agitating the water inside the glasses (Audio CD 3, Track 03). While hitting the glasses, I was trying to record different versions of the sound with different amounts of water each time. Through this process, I was changing the conditions surrounding the sound that was being perceived. This focused the attention of my observations to the conditions that surround a sonic event as a very important factor that shapes the form of the sound we perceive.

The next observation was the sound of an air condition in a small studio. This sound was a low continuous drone (Audio CD 3, Track 01), and was always present in the room. I analyzed the conditions surrounding this sound, and my attention focused on the size of the room in which this sound existed. The size of the space is intrinsically linked to the way we perceive a sound, as the research conducted by Hermann Von Helmholtz in the middle of the Eighteenth Century demonstrates. I wanted to explore how I would perceive this sound if I observed its evolution through smaller spaces (Audio CD 3, Track 02). Through the use of glasses of different sizes I explored the evolution of this sound happening through spaces of different sizes, and observed the change in the pitch of this sound (for example, the recordings demonstrate that the pitch of the sound transmitted trough a glass is higher) in relation to the size of the glass being used.

Another auditory perception was the sound of a helicopter in two different situations: while passing overhead, and while hovering over a fixed spot (Audio CD 3, Tracks 4 and 5 respectively). Fluctuations in the frequency and the amplitude of this sound were observed. When the helicopter is passing over the listener (Track 3), a fluctuation in the base frequency of the sound is heard. This fluctuation occurs because of the effect of the Doppler effect on the shape of the sound, as the helicopter is moving towards, and away from, the listener. When the same sound is perceived when the helicopter is not moving, these fluctuations are still present and are combined with subtle fluctuations in the dynamics of the sound.

The perception of this event in these two different situations reveals the relationship of the evolution of a sound with the medium in which it is being produced. Without the interference of the Doppler effect in the second observation, the factors that are left interfering with the evolution of the sound of the helicopter are the revolving helix of the helicopter, and the movement of the air between the helicopter and the listener. The movement of the air between the helicopter and the listener interferes with the sound of the helicopter in the same way the movement of the water inside the glass interferes with the sound of this glass.

Aim 2:

- To expose the intersections and analogies between the material and the energetic space through the exploration of the physical evolution of sound.

In his paper *Towards a Space – Time Art: Iannis Xenakis' Polytopes*, Sven Sterken looks at Polytopes by Iannis Xenakis through the scope of architectural theoretician Reyner Banham. This theory suggests that the perceived environment can be divided in two spaces: the tectonic or material space, which comprises of physical elements such as the dimensions of a space, other objects in the space etc. The second space is the energetic space, which includes non – material elements that affect our perception of the surrounding environment such as light, temperature, sound and smell.

Sterken explains that in Polytopes, the use of light and sound alters the perception of the surrounding environment by the audience, depending on where they physically stand in the installation. Sterken proposes that this manipulation of elements of the energetic space can alter our perception of the physical space. The present study has expanded upon this theory by focusing on the relationship between a specific element of the energetic space (sound) and its relationship to several different elements of the physical space (size of the space, movement/density of the medium etc.). The works produced as part of this study expose specific correlations between the material and the energetic space, and create aural, or audio-visual, representations of correlations between physical and sonic elements such as density of a medium with the pitch of a sound, or movement of the medium with directionality.

- *Ripples* and *Refractions*

These two works present a relationship between the physical ripples on the surface of a moving medium, and the auditory ripples on the frequency of a sound. A relation between a physical movement and a movement of energy is manifested through the exploration and documentation of the way these two movements interact. *Ripples* presents the relationship of the physical and energetic spaces through the sonification of this relationship with the glissandi that are produced as a result of the movement of the water. *Refractions* represents this relationship with the subtle fluctuations on the dynamics of the sound that is played back through the speakers, and enhances this representation visually through the projection of the shadows of the moving water on the wall.

- *Observing density through standing waves*

This piece explores the correlation between physical density and sonic density. As discussed in the introduction, low frequency sounds can sometimes be perceived as physical sensations. Pauline Oliveros recounts that a frequency of 7Hz was so intense that she could feel her belly shaking. The lower the frequency of a sound is, the denser the sonic experience becomes in terms of its physical presence. *Observing density through standing waves* demonstrates that the pitch of a resonant frequency depends on the density of the medium: denser mediums produce lower tones. This installation is therefore a representation of how sonic density can grow with an increase in physical density.

- *Tonality measured by distance* and *Auditory Rainbows*

These works represent the intersection between physical and sonic dimensions, in terms of size and pitch. *Tonality measured by distance* links the sonic dimension of pitch with the physical dimensions of a space through a system that presents this relationship both aurally and visually. It creates a space in which a natural frequency is amplified, and modulates this frequency through an alteration of this space. The distance a sound travels before it reflects on a surface is linked to the tonality of this sound, and this link is represented through the alterations in the distance between the glasses and the modulations they cause on the frequency the glasses isolate.

Auditory Rainbows presents the correlations between sonic and spatial dimensions through the way tonal dimensions of a sound are shaped by the dimensions of the space through which this sound is transmitted. The piece achieves this by introducing a small space between a sound source (piano) and the listener that can filter sound through its physical dimensions.

<u>Question:</u>

- How can we categorise and explore the intersection of sound with the physical space?

This project divided the general conceptual framework of the intersection of sound with the physical space into two categories: the interaction of sound with the medium through which it is being transmitted, and the interaction of sound with the size of the space in which this sound is produced. These two areas are considered to be the points of contact of the matterial and the energetic space through the medium of sound. The works presented in this thesis fall under these two areas.

- The interaction of sound with the medium through which this sound is being transmitted

Ripples, Refractions, Observing density through standing waves

The first point of contact of the interaction of the energetic and the material spaces, demonstrated through the medium of sound, is the relationship between sound and the physical medium in which this sound is being transmitted. Sound cannot exist in a vacuum and always needs a medium through which it can travel. Therefore sound will always interact with the molecules of this medium. Each of the works included in this conceptual framework explores different aspects of the relationship between a physical medium with the sound that is transmitted through this medium. These works place a medium between a sound source and a listener and explore the relationship of this sound with the density and the movement of this medium.

- The interaction of sound with the space in which this sound is produced.

Tonality measured by distance, Auditory Rainbows

This is the second point of contact between the material and the energetic space through the medium of sound. The size of the space in which a sound is produced always leaves an imprint on this sound. The works in this framework explore this imprint by creating systems that involve closed spaces that interfere with a sound that is being transmitted from a source to an audience.

<u>Aim 3:</u>

- To explore the aforementioned areas through the practice of composition and sonic art.

As mentioned previously, this study has produced several works that follow different formats, ranging from experimental compositions to sound installations. Each work is dealing with a specific aspect of the evolutionary process of sound and the secrets it reveals about the relationship of sound with the environment that surrounds it. In doing so, various compositional strategies and creative methodologies have been applied. This research project looks at the works of a variety of sound artists and composers working in different fields of sound art, experimental composition and electroacoustic composition, in order to find appropriate representational methods for the evolutionary processes of sound.

One element that was used extensively in this thesis as a tool for the representation of the evolutionary processes of sound was sonic feedback. This is an element that some sound artists and composers have used in their work in order to explore and amplify imperceptible sonic phenomena: Alvin Lucier has used sonic feedback in pieces such as *Bird and Person Dinning* (1975) for example, and Sato Minoru in his pieces *NRF Amplification* (2005) and *Observation of Thermal States through a Stationary Wave* (2008).

Their use of sonic feedback has informed this research project, and sonic feedback has become a central element in most of the works presented in this thesis. The works produced as part of this study explore techniques that the aforementioned practitioners have employed in order to produce, control, and manipulate sonic feedback. In some cases these techniques were extended in order to focus on the evolution of sound in a space, and create metaphors for the representation of elements that affect this evolution. In *Tonality measured by Distance* for example, the concept of using small vessels to produce and manipulate sonic feedback was extended in order to create a system that changes the frequency of this feedback in real time, while also creating a metaphor for the relationship between a sound and, the space in which this sound is produced.

Questions:

- How can we employ these observations in the compositional process as a means of using the physical behaviour of sound in order to manipulate an acoustic signal?

After the perception of these phenomena, their effects were recreated in controlled experiments in order to analyze them and understand which parameters of the sound they affected. The fluctuations heard in the sound of the helicopter and in the sound of the clinking glasses engaged me with the exploration of sounds being transmitted through a moving medium. The sound of the clinking glasses was analyzed in order to understand what these fluctuations were. Through the analysis of this sound I established with certainty that the fluctuations in the frequency of the sound of the glasses did occur.

In order to magnify these fluctuations, I time-stretched the sounds and prolonged the fluctuations in their frequency. Through this process, I wanted to hear the range of the glissandi and observe how much the movement of the medium can affect the frequency of the sound. I presented this process of exploration of 'zooming in' on a phenomenon through time-stretching a sound in order to hear its evolution to an audience, in the context of the electroacoustic composition *Ripples*.

The perception of the fluctuation of the frequency of the sound coming out of the glasses was further developed in the sound installation *Refractions*. Through the practical experimentation of moving the glasses backwards and forwards while hitting them in order to agitate the water, I developed a system that agitates a medium through the use of boxes connected to windscreen wiper motors that cause the boxes to rock backwards and forwards. The experimentations with a sound being transmitted through a liquid medium led to the development of the sound installation *Observing density through standing waves*. This sound installation uses a combination of three different liquids and the medium of air, in order to demonstrate the way the evolution of a sound relates to the density of the medium through which this sound is being transmitted.

The perception of the sound of the air conditioner were developed through practical experimentation in two sound installations, and one composition. A way of amplifying the natural resonant frequencies of a closed space through sonic feedback was revealed during the process of using glasses of different sizes in order to observe and record the sound of the air condition as it evolved through spaces of different sizes. I engaged in practical experimentations with sonic feedback, and explored the way I could shape it through my physical interference with the glasses by moving my hand above the glasses (Audio CD 2, Track 3).

This process was developed in the sound installation *Tonality measured by distance*, in which two glasses interact with each other in the same way that my hand was interacting with the glass during the initial experiments: by constructing a system that moves a candle glass above the glass that instigates the feedback loop. The use of closed spaces, in combination with tie clip microphones and speakers that instigate a feedback loop, also informed the development of my sound installation *Observing density through standing* waves. In addition, combinations of the feedback loop produced in closed spaces with other sounds have been practically explored (Audio CD 2, Tracks 1, 2, and 6).

The observation of the way the glass could isolate frequency components from the sound of the air condition, and amplify them to a feedback loop, led to the experimentations of the interaction of this feedback loop with external sounds. These experimentations were developed in the composition *Auditory Rainbows*. The experimentations with closed spaces of different sizes that amplify a resonant frequency are also currently being developed in another composition with the provisional title *A study of orchestration in the physical space* (a preliminary recording of this composition is included with this thesis on Audio CD 2, Track 4). This composition will use vessels of different sizes that instigate feedback loops, and then transfer each feedback loop from one vessel to the other. In doing so, this piece aims to explore how the timbre of a sound can be manipulated in the physical space.

- Which compositional practice, or practices, can provide a context for the exploration of the intersection of the physical and energetic space through the medium of sound?

In dealing with such a multilayered concept, this project looked at different representational methods from the fields of electroacoustic composition, experimental composition and sound art. Each of these fields has provided each work produced as part of this study with a different mode of representation of the evolution of sound. The project begins with the observation and representation of this evolution through the use of technology. The field of electroacoustic composition was explored in order to investigate ways in which this evolution could be represented through the use of music technology. The first observation of the phenomenon of sonic refraction as it was demonstrated through the resonant decay of the sound of a glass engaged me in a research of sound works that explore sounds with long, resonant decays. This research led me to two works by Christina Kubisch and Jonty Harrison, entitled *Dreaming of a major third* and *Klang* respectively.

This project however focuses on the presentation of the evolutionary process of a sound through acoustic phenomena. In order to work towards such an aim, the project looks at the works of composers and artists whose work explores natural phenomena and their representation. Sound artists and composers Alvin Lucier, Sato Minoru, Toshiya Tsunoda and Carsten Nicolai provide the general underlying context of this project as their work is specifically concerned with the representation of acoustic phenomena and natural processes.

Michael Nyman classifies Lucier as an experimental composer[37], as he is using unconventional means for the production and organization of sound but his work is usually presented in a concert setting. Minoru and Nicolai are classified as sound artists[38]. However, both Minoru and Nicolai engage with the representation of natural phenomena through different kinds of activities such as sound installations, performance, writings, or visual works. Through

[37] Michael Nyman, 1999, *Experimental Music: Cage and Beyond*, Cambridge University Press

[38] Hatanaka Minoru and Nozaki Takeo (editors), 1999, *Sound Art – Sound as Media*, NTT Publishing Co. Ltd.

their practice they use different methods of representation that are associated with different fields of artistic practice.

This research project follows this approach, and engages in activities relating to different sound-making practices in order to create representations of the evolution of sound, and the intersection of this sound in the physical space. *Ripples* engages in such a representation through the presentation of the sound on which the evolution of sound was observed to an audience in the context of electroacoustic composition and through an experience of this sound removed from its source, through acousmatic listening.

Auditory Rainbows is located in the field of experimental composition as it uses unconventional means for the production and organization of sound, and the result of this process is presented to an audience in a concert setting. *Tonality measured by distance, Refractions and Observing density through standing waves* are located in the field of sound art as they are sound installations that integrate elements from sculpture, and are not sound pieces of a specific duration presented in a concert setting. All these works come together under the territory of “evolutionary sonology”, which engages with different elements from the practices of electroacoustic composition, experimental composition and sound art in order to create metaphors for the evolution of a sound in the physical space.

Appendix I

Glossary of Terms

Beats: When two sine tones with similar frequency are combined, what we hear is a sound whose frequency fluctuates rapidly, and this fluctuation results in a pulsating effect on the tone we are hearing. Beats can also result between sine tones of the same frequency, but different phase.

Doppler Effect: The Doppler Effect (named after Christian Doppler) is the shift in the frequency that occurs when a sound source is moving towards, or away from, a listener. Sound waves are spread in homocentric circles around the sound source, much like the waves a pebble produces when we drop it in water. When the source of the sound is moving, the sound wave is compressed on the front side, causing the frequency to rise, and spread on the other side, causing the frequency to drop.

Natural Resonant Frequency: Natural resonant frequency of a space is the frequency component that this space will amplify if a sound is produced in the space. This frequency is related to the size of this space.

Pure Wave Oscillator: An oscillator that generates a sine wave; a continuous tone with fixed amplitude and frequency.

Refraction: When a sound passes from one medium to another, the direction of the sound changes. This happens because of the reflection of sound when it passes from one medium to the other.

Sine Wave (sine tone): A sinusoidal wave is a sound wave of fixed amplitude and frequency, a steady tone. The sounds in nature are composed by different frequencies, of different amplitudes, that tend to alter with the course of time. The sine wave is single frequency, whose amplitude and phase remain fixed.

Sonic Interference: Sonic interference is the interaction between two sound waves; when two sound waves have the same frequency they can produce two types of interference: constructive and destructive interference. In constructive interference the sound waves have the same phase, reinforcing each other. Destructive interference occurs when two sound waves have opposite phases and cancel each other out.

Standing Wave: Standing wave is a sound wave resonating in a space; when a continuous sound is projected in a space and reflects on a surface, a continuous resonating wave is created in the space through constructive and destructive interferences.

Appendix II
Resources

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Appendix III

Media Index

DVD – Video Documentations

- Tonality measured by distance ……………………………………….. 03:15
  Sound installation
- Refractions ……………………………………………………………… 03:46
  Sound installation
- Observing density through
  standing waves …………………………………………………….... 02:38
  Sound installation
- Auditory Rainbows process ………………………………………… 02:55
  Video documentation from the
  exploratory process for *Auditory Rainbows*

Audio CD 1 – Compositions

1. Ripples ………………………………………………………………… 06:36
   Electroacoustic
   composition
2. Auditory Rainbows …………………………………………………… 08:07
   Experimental Composition for
   piano and resonating glasses
   (live version)
3. Auditory Rainbows …………………………………………………… 08:20
   Experimental Composition for
   piano and resonating glasses
   (studio version)

Audio CD 2 – Research recordings

1. A white noise mass ………………………………………………….. 05:22
   Improvisation with resonating glasses
   and electronic soundscapes (version 1)
2. A white noise mass ………………………………………………….. 05:22
   Improvisation with resonating glasses
   and electronic soundscapes (version 2)
3. Four small Well Tempered spaces ………………………………… 10:44
   Improvisation with the use of resonating
   glasses as musical instruments

4. A study of orchestration in the physical ……………………………… 16:11
   space (working title)
   Work in progress that explores the manipulation
   of sonic timbre through the use of resonating
   vessels of different sizes

5. Observing density through standing waves ………………………. 01:24
   Short recording of the sound installation at
   the Global Composition 2012

6. Vocal Experiments ………………………………………………….... 01:26
   Experimentation with voice and a
   resonating glass

Audio CD 3 – Field Recordings

01. Air condition ………………………………………………………….. 00:24
    Short recording of the sound
    of an air condition unit

02. Air condition 2 ……………………………………………………... 00:25
    The sound of the same air
    condition unit, recorded through
    a glass

03. Wineglass …………………………………………………………….. 00:24
    Recording of a glass filled with
    water and hit with a drumstick

04. Moving Helicopter ………………………………………………… 00:17
    A helicopter passing overhead

05. Steady Helicopter …………………………………………………. 00:37
    A helicopter hovering over a
    fixed spot