COMPOSING FOR THE PERFORMANCE SPACE

A PRACTICE-BASED INVESTIGATION ON THE DESIGN OF INTERFACES FOR SPATIAL SOUND AND LIGHTING

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Composing for the Performance Space: A practice-based investigation on the design of interfaces for spatial sound and lighting

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ABSTRACT

This thesis presents a compositional portfolio that incorporates design methods for creating interactivity between music, spatialised multichannel audio and lighting. This is presented in the form of musical scores, commentary, and a summary of interfaces for sound spatialisation and lighting, including technical studies that present new design concepts and industrial prototypes. Furthermore, it reveals a new mixed-media format, *Sound Canvas*, that can be used for the display of interactive music and sound art within galleries.

Spatial music has, for some years, been extensively explored in experimental music through different analogue and digital systems. Examples can be found in the electroacoustic works of Schaeffer (e.g., *Symphonie Pour un Homme Seul*, 1951—performed through the 'space potentiometer' device), Stockhausen (e.g., *Gesang Der Jünglinge*, 1955-56; *Oktophonie, 1991*), Xenakis (e.g., *Bohor, 1962; Hibiki Hana Ma, 1969-70*), and in the sound installations of Bernhard Leitner (e.g., *Double Arching*, 1999; *Sonambiente*, 2006). The technology available today allows composers to use not only what is commercially available, but also to implement their own systems for spatialisation and performance interaction. The expansion of new audio codecs and microcontroller technology offers new possibilities to be musically explored.

Similarly, current stage lighting technology can also be explored further through experimentation. Whereas stage lighting in popular music has been commonly explored by lighting designers, this has not been widely investigated in contemporary music. By using software such as Cycling '74's Max and open-source hardware platforms such as the Arduino, composers can design their own interfaces for sound-light control.

These two forms of expression—space and light—allow composers to move beyond traditional notation and create sound interactions within the performance space, which can become multisensory and yield new forms of artistic expression. Taking practice-based and applied research strategies, this thesis suggests new ideas for the two mediums and narrates the process of development through design.

Keywords: sound spatialisation, sound-light interaction, interactive composition, music interface design, performance space, multichannel audio, multisensory music, sound canvas, mixed-media art, kinetic music, kinetic sound art, virtual concerts.

DECLARATION

I hereby certify that this thesis constitutes my own product, that where the language of others is set forth, quotation marks so indicate, and that appropriate credit is given where I have used the language, ideas, expressions or writings of another.

I declare that the dissertation describes original work that has not previously been presented for the award of any other degree of any institution.

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PREFACE

This research arose from a desire to comprehend how various aspects of the performance space—particularly spatial audio and light—interact with music. It began with investigations around the concept of music *stasis*; the idea that music events can stop or be constrained—e.g., by sustaining chords. During these studies, I realised that sound, when placed in different physical locations, can create geometry and function as a very different medium than the traditional. Experiments with this type of abstraction I called 'static music', which were conducted by myself and exhibited in a solo exhibition in 2014. This exhibition presented *Bamboo Heaven*—a work for eight bamboo flutes which were automatically played by air pumps—*Earphones*, an installation with 180 earphones hung on a suspended ceiling—and among others works, *Collage #1*, the first *sound canvas* experiment. This artwork presented eight speakers hidden behind a black canvas, which simultaneously played the sounds of birds and insects. This material was later presented to members of the music department at the University of Liverpool, and I was invited by Professor Matthew Fairclough to continue this research formally at the University of Liverpool.

Therefore, the impetus for my research, which began in 2015, was essentially the desire to create music that could explore space and find the technology to realise the concepts I envisioned. When I joined the Transformation North West doctoral programme in 2017, it further developed to an inquiry of the design of tools for musicians to take control of light and space. Design became an important part of the research, and a further understanding of electronics was required to be able to collaborate in projects with industries in the North West.

The addition of 'lighting' as an element of investigation became important as projects developed. The use of light in projects was initially introduced to support the experience of spatialisation, since signalising with lights the location of a sound source in a room or artwork with multiple speakers can assist and stimulate the audience's perception[1]. This made me realise that light can be as important as spatialisation for a composer who wants to write for

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[1] Although my aesthetic aim has been to indicate the location of sound sources, it is important to note that spatialisation can also be used for 'masking' or concealing source location.

the performance space. Furthermore, it showed that the use of lighting shares similarities to the use of spatial sound[2], and this prompted further examination.

Throughout this investigation, in addition to being a researcher and composer, I felt like an electrical engineer, a designer, a programmer, and even a visual artist—e.g., over a hundred circuit boards were designed and assembled for the *Sound Canvas* project, which also included frame modifications, 3D printed parts, the use of fabric and other materials, not to mention mounting easels and preparing work for exhibition.

I hope the knowledge gathered here through composition and other practice-based experiments can be valuable for musicians, sound artists, designers, scholars, and the general art community.

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I am thankful to Professor Nick Dunn, along with all other members of the Transformation North West board and cohort. My appreciation extends to the NWCDTP, AHRC and UKRI, for generously funding this research and for opening several doors for training and networking. Finally, I would like to thank my wife, Raquel Costabile, and my friend Ben Vitteau, who supported me all along with their inspirational thoughts.

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[2] To mention one example, the kinetic effect of light ‘chasers’, where one light instrument appears after the other in sequence, can be similarly achieved with loudspeaker panning.

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1 Introduction

This practice-based research has investigated the use of spatial sound and lighting in composition, exploring digital technology and new concepts of sound interface design. It presents a documented portfolio of approximately 60 minutes of music, including scores and textual analysis. It has also engaged with applied methodology through a doctoral programme (Transformation North West) which aimed to create collaborative design projects between students and industry based in the North West of the UK.

Spatial music has its roots in polychoral music of the 16th century, and it proliferated in the music of 20th century composers with new developments, such as by combining different ensembles around the stage (e.g., Stockhausen's *Gruppen*), providing stage direction to performers (e.g., Xenakis' *Eonta*) and making use of new technology—i.e., multichannel electroacoustic music (Harley, 1994). The advances in digital technologies and ever easier access to them in the 21st century, has enabled many artists to make use of sensor technology, real-time analytics, wireless networks and to engage in a variety of new possibilities that have been shaping contemporary aesthetics. With the expansion of the technological generation, inquiries for further investigations concerning how sound spatialisation can be applied and what is currently being developed by the creative industries, are rich in possibilities.

Similarly, stage lighting has developed significantly in the 20th century, motivating composers—e.g., Scriabin—to experiment with multisensory score notation. Today, the implementation of communication protocols such as DMX allow composers to explore this interaction even further, developing new types of sound to light interfaces.

Both fields of spatial sound and lighting interchange ideas which can be further explored and that can offer new insight for multisensory aesthetics. Furthermore, despite the advances in technology, there are still limitations that can impede composers to achieve their goals. This entails further investigation, which can be empirically achieved through tangible practice and live performances. Therefore, the projects and compositions presented through this research aimed to provide knowledge and insight that can be useful in the fields of composition, as well as design ideas for new sound interfaces.

The two themes of exploration, spatial sound and lighting, are here classified as elements of the 'performance space'. The performance space, or the place where a piece of music is performed, can also involve other visual, architectural, or acoustic elements—e.g., screen projection, scenery, acoustic panels. However, sound spatialisation and light can be treated as instrumentation, since both can create abstract gestures and discourse in space around the performer and audience, alongside music.

In some projects, the performance space is also explored in other contexts: the virtual and the exhibitive. The virtual is demonstrated by the online performances of *Future Lights* (5.5) and *Intersidereal* (5.6). The exhibitive is presented by the *Sound Canvas* project (5.7), which provided a mixed-media system for listening to recorded music, especially music with lights and spatial sound which cannot be fully experienced through standard sound systems.

The *Sound Canvas* research concludes with several design prototypes of compact and battery-powered multichannel interfaces. This offers several advantages in the sound exhibition domain, not only for artists but also for creating original sound exhibitions that can be used to engage new communities. For instance, allowing soundscapes to exist side by side on the walls of an exhibition room can offer a traditional gallery narrative to people with visual impairments, who would not normally have access to this.

1.1 Questions

Due to the practice-based nature of this research, questions emerged during the course of explorations, projects and performances. The key questions relate to compositional aesthetics (e.g., multisensory creations of light and space) and design (e.g., the creation and use of interfaces). The three main queries investigated were:

1. What new musical concepts can be found through the incorporation of spatial sound and light into compositions and installations?
2. How can spatial sound and light be controlled by performers and what types of interaction (mapping) can be created?
3. What new interfaces can be designed for spatial sound and light control?

In addition, a historical investigation was necessary to understand how composers realised spatial and sound-light works with analogue or early digital technology.

1.2 Contributions

The intention of this work is to contribute new aesthetic concepts concerning spatial sound and lighting in composition, providing notions and methods that can be reutilised by other composers. It demonstrates multisensory possibilities through several examples of light and sound interaction, and it shows how composers can learn from the lighting design field and take control of stage lighting. In addition, it has provided methods for the exhibition of composition and sound art in galleries.

Finally, participation in the Transformation North West projects was beneficial to companies in the region, particularly by providing commercial prototypes and R&D.

1.3 Scope

This research demonstrates an art portfolio and critical reflection, focusing on composition, sound art and design. It presents a commentary on the development of the projects presented. It assumes that the reader has some musical knowledge as well as a basic knowledge of electronics.

Although this work includes notes about electronics and technology, it does not take a scientific or engineering approach. It does not include all the calculations, schematics, programming codes and formulas taken to achieve the objectives. Furthermore, basic knowledge of sound spatialisation is provided; however, this is not presented in-depth, to the extent that would be expected in the field of computer science or acoustics. References are provided for those who want to expand their knowledge beyond what is presented here.

2 Space, Light and Design

This chapter aims to provide a literature overview of the progress of composition alongside spatial sound, lighting, and design. It provides a brief history of these developments and demonstrates compositional cases in which composers required new technology in order to achieve their aesthetic goals.

2.1 Space

The performance space, or the place where music is performed, can have different sound configurations. As humans are able to localise sounds as auditory objects in space, the position of the sound source can be significant or even essential to a piece of music. The positioning or spatialisation of sound can enhance music or communicate new forms of abstractions. This has been explored extensively throughout the history of music, with clear examples observed as early as the 16th century, when polychoral music was performed (Roads, 2015; Shephard and Leonard, 2014). As ensemble and orchestras progressed, seating plans were initially designed to group instruments, equalising acoustics and developing contrasts between timbre. In the 18th century, many types of orchestral configuration were common: amorphous, single rows, semicircles, around tables, in tiers, etc. (Spitzer and Zaslaw, 2004).

In addition to placing musicians in different locations, musical dialogues between spaced instruments can produce efficient localisation contrasts. This was further explored in the 20th century, evidently in the music of Charles Ives (e.g., *Fourth Symphony*), Henry Brant (e.g., *Ice Field*) and Stockhausen (e.g., *Gruppen*) where musicians could be found scattered around the concert room or organised by multiple orchestral groups with more than one conductor Mobile instrumentation—where musicians move along the stage—can be observed in the music of Xenakis (e.g., *Eonta*), Berio (e.g., *Circles*) and Boulez (e.g., *Domaines*) (Roads, 2015, Harley, 1994; Shephard and Leonard, 2014).

In the examples mentioned above, the concept of design in relation to sound and space exists in the form of instrumental notation. With cinema applications and the advent of loudspeaker systems in the 1930s, audio engineers began developing multichannel audio tools. In this decade, stereophonic techniques were developed by Alan Blumlein and Harvey Fletcher, and in the late 1950s two-channel equipment became available on the market (Valiquet, 2012).

The need for multichannel technology for music performance became evident in a few events that happened in the 1950s. In 1951, Pierre Schaeffer performed a composition through a new device called *potentiomètre d'espace* ('space potentiometer'). This device was designed by the engineer Jacques Poullin, who worked with Schaeffer in the Groupe de Recherches de Musique Concrète, offered by the Radiodiffusion-Télévision Française. It allowed a performer to control the trajectory of sounds between four loudspeakers (Valiquet 2012; Roads, 2015, Palombini, 1993).

Still in the 1950s, further compositional experiments with multiple speakers took place in a concert organised by John Cage at the University of Illinois, which included the music of Boulez, Messiaen, Schaeffer and Pierre Henry. Eight speakers were arranged in a ring around the audience. With the absence of commercially available eight-channel systems, each speaker was individually connected to a single-channel tape machine (Valiquet, 2012).

In 1956 and 1958 multichannel compositions were projected in a larger scale. In 1956, *Gesang der Jünglinge* by Karlheinz Stockhausen was projected over five groups of loudspeakers in the auditorium of the West German Radio (Roads, 2015). In 1958, the composer and architect Iannis Xenakis designed the Philips Pavilion at the Brussels World's Fair. Inside the building, it is estimated that about 350 loudspeakers operated through an 11-channel sound system. Xenakis's *Metastasis* and Varèse's *Poème Electronique* were projected in the Pavilion, shifting between groups of loudspeakers. This spatialiser system was created by Philips engineers and was manually operated through rotary telephone dials, which allowed switching between groups of 5 speakers at a time (Drew, 2010; Roads, 2015).

Stockhausen was a composer who since the mid-1950s experimented extensively with sound spatialisation. He initially used four-track tape recorders by Albrecht and Telefunken (Decroupet, 2018) and for the West German Pavilion at the 1970 Worlds' Fair in Osaka he co-designed a multichannel mixing desk with technicians from TU Berlin and Siemens. This desk included 14 input channels (7 microphone and 7 line channels), as well as 7 outputs with high-pass filters and an additional output with a low-pass filter for the subwoofer (Williams, 2015).

Other significant studies of sound spatilisation were conducted by Berrnhard Leitner in the 1970s and applied in the sound art domain. Leitner produced in his studio several studies in a variety of spatial arrangements, taking sound as an architectural material to create sound spaces. Some of his experiments surrounded the audience with geometric shapes, such as cubes, spirals, tubes, and others (Licht, 2007). In 1971, Leitner described his '*Soundcube'* concept:

> The *Soundcube* has a grid of loudspeakers on each of its six walls. The dimensions of the cube depend upon the particular situation. It is ideally "neutral" visually speaking, i.e. without any specific spatial message. The sound is programmed to travel from loudspeaker to loudspeaker. An infinite number of spaces or spatial sensations can be created. (Leitner, 1971)

Taking into consideration that the design counted with 384 individually controllable loudspeakers, the concept of the *Soundcube*, along with many other sketches by Leitner, were unachievable, as accessible technology at this time was still limited to four-track tape recorders—recorders with more tracks did exist, such as the Ampex MM1000 from 1967, however these machines were expensive and large to transport (Hurtig, 1988).

A *Soundcube* installation displayed at the Museum moderner Kunst in Vienna in 1981 shows a more feasible sound space with six loudspeakers (Leitner, 1981). Leitner does not describe what equipment he used for his early installations, however, a photograph of his work *Expanding / Contracting* from 1979 (Leitner, 2008, p.148) shows a Sony TC-788-4 four-track tape recorder and two Sony TA-F6B amplifiers. This indicates that despite his ambition to create complex sound spaces, Leitner did not work with engineers or bespoken technology and was utilising what was commercially available. Furthermore, it is probable that his use of technology remained the same throughout his career, as in 2004 an installation for 40 channels made use of a pair of a Fostex HD 2424LV and a 40-channel amplifier (Leitner, 2008, p.148).

As the industry for multichannel technology progressed, it became smaller and lighter, presenting itself in the form of compact cassette technology in the 1980s (notable with new multitrack equipment by companies like Fostex) and gradually reaching the digital, which was strongly established in the 1990s (Fostex, n.d.). Today, computer technology is combined with a myriad of multichannel options, such as multichannel USB interfaces and mixing desks. Several theatres around the world are equipped with dedicated equipment and there are theatres (e.g., Audium in the US) designed especially for multichannel sound performance (Cohen and Martens, 2020). Several techniques for sound spatialisation—e.g., VBAP, HOA, WFS (Roads, 2015)—have been developed and multichannel audio has been extensively explored by composers.

Much more could be said about the history of multitrack recorders or multichannel technology (see for example ‘Articulating space’ in Roads, 2015), however, this goes beyond the scope of this research. This section aimed to show how important multichannel technology has been for composers and sound artists since it began. Furthermore, it has demonstrated the limitations that artists must have faced when attempting to realise spatialisation concepts when technology was either not available or still in development.

2.2 Light

> Light is the sister of music… To reinforce the crescendo of the one by strengthening the other, to harmonise all their qualities of shading, phrasing, and rhythm, would be to convey to an audience, by a combination of sound and light, a maximum of aesthetic sensation and to provide actors with undreamt facilities of expression. (Jaques-Dalcroze, 1973, p.130)

In the earliest stage performances, lighting existed mainly through oil lamps and candles. In the 19th century, the introduction of gas devices allowed dimming, thus intensity could be varied, and colours blended. Limelight also made an entrance, but it was quickly substituted by electric light towards the end of the century (Applebee, 1946).

Certainly, lighting had been a preoccupation of many composers in the past, especially for opera performances. Debussy clearly showed his stage lighting concerns on the performance of *Pelléas et Mélisande* at Covent Garden in 1909. During the rehearsals, he wrote that Act 1 was not “sombre enough” and Scene 3 should suggest “twilight”. He also noted that the sun should diminish in intensity while Mélisande sings: ‘*Il descend lentement, alors c’est l’hiver qui commence*’ (Orledge, 1982).

Music became more involved with lighting through the influence of Adolphe Appia, who was a stage lighting theorist seeking to strengthen the relationship between music and light. Appia worked on the stage production of some Wagner’s operas in the early 20th century, approaching more dynamic means for illuminating the performances (Kernodle, 1954). In his book ‘Musique et mise en scene’, written in 1897, Appia proposed that the union between light and music could become more dynamic: ‘This relationship will allow us to utilise music and lights simultaneously, as a single art, and act sovereignly on our personality’—‘*Cette relation va nous permettre d’utiliser la musique et la lumière simultanément, tel un seul art, et agir ainsi souverainement sur notre personnalité*’ (Appia, 1988, p.167).

However, the interaction Appia envisioned was still far from what could be achieved; his way of connecting the mediums was purely expressed by painting the scenes according to the theatrical drama and extramusical context; there was no objectivity for working with absolute or instrumental music.

The idea of light in music becomes more formalised in Scriabin's *Prometheus,* composed in 1910. This composition includes in the score 'light' as an instrument, with colour indications for different sections. The first performance of Prometheus with light was held in 1915 at the Carnegie Hall in New York (Galeyev, 1988). Several other explorations between colour and music have been conducted throughout history and various designs for light instruments or 'colour organs' were patented (Betancourt, 2004).

The use of light in music was widely studied by the group Prometei, founded in 1962 at the Kazan Aviation Institute in the USSR (Russia). There they examined 'music-kinetic art', creating many devices such as *Prometei 1*, *Prometei 2* and *Crystal*. *Prometei 1* was a colour organ for screen projection. The other two devices were constructed to create light and sound interactions such as: '(1) light brightness with music volume or loudness, (2) hues with timbre and chords, (3) structures of images with metre or rhythm and (4) spatial character of drawings with melody' (Galeyev, 1976).

Interfaces for sound and light were for many years expensive and heavy (Galeyev, 1994). Commercial devices such as 'light organs', which pulsate light according to the music's amplitude or separate colours by sound frequency bands became popular in the 1970s in discotheques. In the 1990s, digital technology for light and sound interaction was still developing. Composers working with electroacoustic music and the MIDI protocol created digital interfaces, however, establishing communication between devices was still a complex task—e.g., the work of Mclean shows the intricacy of connecting a computer to a light panel matrix (Mclean, 1992).

Today, the industry of stage lighting is vast, presenting several types of lighting instruments and accessories (e.g., floods, spotlights, beam lights, gobos, fog machines, diffusers, etc.), in addition to control systems for manually operating lights or triggering presets. The LED innovations and the DMX512 protocol for digital communication facilitate light control, and software allows lighting to be digitally plotted in three dimensions.

It is important to add that with the progress of VJing technology and software such as Max (with Jitter integration), composers have been exploring immensely the use of projections for combining audiovisual interactive content (see for example Lund, 2016). However, this approach is different from the use of light as individual elements, in Mclean words: ‘While pixels in a computer-graphics or video work might also fit these criteria, they differ in that they are not perceived nor are they meant to be perceived by viewers as individual, discrete elements.’ (Mclean, 1992)

As dynamic lighting has been strongly associated with rock concerts (see for instance Reid’s explanation of a ‘rock board’ in Reid, 2001) and lighting for concert music is often controlled by a production team or technicians, composers do not normally become involved. However, with the technology available today, it is possible for composers to take control over some lighting instruments and operate them through their own digital interfaces (at least at a basic level, which does not require the expertise of a lighting designer).

This section has shown the historical importance of light to music composition and how interfaces for light-sound interaction have become more accessible to composers in the last decades.

2.3 Design

Design can be seen as the process of construction of objects or mechanisms (products, systems, networks, places, etc.) or the elaboration of a plan for a determined end. The word ‘design’ originates from ‘disegno’ in Latin, meaning ‘drawing’. Prior to the 18th century, the idea of design originated from the arts of drawing, particularly in three forms: painting, sculpture and architecture. This original meaning of design was transformed due to mass production and an industrial meaning emerged throughout the 19th century (Macdonald, 2004). Today, the scope of design branches is vast; to mention a few: graphic design, web design, software design, circuit design, product design, interior design, fashion design, engineering design, sound design.

For every craft there is the need for tools and design often operates as a process aiming to solve a problem. In painting, there are several noticeable examples. The refinement of a brush as a tool, through rethinking materials and techniques, solved problems for artistic representation. In a similar manner, oil painting techniques that were established in the 16th century supported the ambition of an accurate representation of our visual reality (Stratton, 1996). Thus, brush, paint, canvas, all objects that supported the constitution of the final medium have been subject to design thinking, resulting in solutions and innovative aesthetics.

In music, instruments have been designed and redesigned for facilitating human interaction or for aesthetic reasons. The invention of valves for brass instruments in the 19th century significantly changed orchestration, allowing the use of a wider register and chromaticism, resulting in a new path for ideas that have supported the aesthetics of Romanticism (Jackson, 2005). In this same period, inventions for recording and reproducing audio were emerging. The phonograph, invented by Thomas Edison in 1877, inaugurated a new path to music technology, being followed by a myriad of new designs which intended to improve sound recording capabilities (Burgess, 2014).

Beyond the importance of mechanical design, the fast evolution of electrical engineering delivered a wide range of instruments and audio devices. This includes loudspeakers, microphones, synthesisers, samplers, effects units, mixing desks, etc. In the final decades of the 20th century, reasonably fast computers allowed musicians to work digitally through programming languages and software, allowing new methods for audio recording, score notation, composition and performance (Collins, 2017; Essl, 2017; Wang, 2017).

The development of electronic and digital tools for artistic applications progressed throughout the 21st century. However, this century has presented a new trait: artists have now wide access to tools that can assist in the design of their own custom technology. In the 1990s software for music and interaction such as Pure Data and Cycling '74’s Max began to revolutionise the way composers worked and became increasingly popular (Wang, 2017), reaching the curriculum of many music schools and a variety of universities worldwide (Cycling '74, n.d.a.). This digital knowledge was boosted in the 2000 and 2010 decades with new inventions that went beyond the software side: the Arduino and Raspberry PI platforms, which paved a new path to experiment with hardware and gave artists straightforward access to sensor technology and electrical engineering knowledge (Jordà, 2017).

This digital revolution was further reinforced by the commercialisation of low-cost 3D printers in the 2010s, which allows hardware enclosures and a variety of tools to be made by artists, including new instruments and wearable accessories (Freedman, 2018). Those aspects of design integration into the music world have been strongly supported by *maker* communities working with a variety of new microcontrollers, printed circuit boards and open-source codes, which facilitated the dissemination of this DIY technology (Richards, 2017).

3 Methodology

This chapter explains the methodology taken throughout this research. It involves two main approaches: practice-based and applied research.

3.1 Practice-Based Research

This research has prioritised a practice-based methodology, which has also been referred to as "practice-led research", "practice-centered research" and "studio-based research" (Niedderer and Roworth-Stokes, 2007). Here the term "practice-based research" is reserved to:

> …an original investigation undertaken in order to gain new knowledge, partly by means of practice and the outcomes of that practice. (Candy and Edmonds, 2018)

Since it is fundamental that practice-based research concentrates on elements of practice, it is common to employ this methodology in the arts. In particular, the field of music composition expects research to include performances and the production of musical scores.

Practice-based research can be divided into two categories: practice-and-research, and practice-as-research. Practice-and-research aims to incorporate practice alongside textual analysis, whereas practice-as-research consists of the entire practice as the final output, without requiring critical exegesis (Skains, 2018). This research takes the first approach, thus incorporating textual analysis to inform how projects engaged with the research inquiry and to build knowledge on the practices of composition and design.

This methodology is appropriate as artefacts created by artists often go through processes that involve issues, problems, and solutions. Therefore, these creational narratives become research material rather than responding to gaps in literature or aiming to respond to problems that are not related to the artefact in question. In the words of Candy and Edmonds:

> A basic principle of practice-based research is that not only is practice embedded in the research process but research questions arise from the process of practice, the answers to which are directed toward enlightening and enhancing practice. (Candy and Edmonds, 2018)

The proposed theme of investigation required multichannel audio and light systems to be developed or tested alongside projects. This reflects the use of recently developed technology (e.g., microcontroller boards, LED lights and sensors) that has not been thoroughly explored and thus this query can provide a pathway for designers and artists. One of the key bodies responsible for this research fund, the Arts and Humanities Research Council (AHRC), encourages realistic research assuming that the method and textual analysis are documented:

> Creative output can be produced, or practice undertaken, as an integral part of a research process... The Council would expect, however, this practice to be accompanied by some form of documentation of the research process, as well as some form of textual analysis or explanation to support its position and as a record of your critical reflection. (AHRC, 2020)

Here the basis of research practice is demonstrated through a portfolio of original compositions, art installation projects and industrial prototypes. The documentation of these projects is provided in the form of music scores, images, performance recordings, and descriptions of the technology utilised. Critical reflection accompanies the narrative and outcomes reveal results and findings.

3.2 Applied Research and Transformation North West

This research was supported by Transformation North West (TNW), which is funded by AHRC National Productivity Investment Fund (NPIF) and is part of the North West Doctoral Consortium Training Partnership. The TNW consists of an interdisciplinary student cohort of twelve members with a common interest in design and technology. This includes students from five partner institutions: Liverpool, Manchester, Manchester Metropolitan, Salford and Lancaster universities. In support of the Industrial Strategy, Transformation NW aims to increase development and prosperity in the UK’S North West (NWCDTP, n.d).

The TNW programme welcomes practice-based research but focuses its programme on applied research methodology, as it aims to finds solutions to promote growth in the region. In simple terms, applied research can be seen as:

> Applied research aims at finding a solution for an immediate problem facing a society or an industrial/business organisation… (Kothari, 2004)

The programme does not determine a specific question; however, it implies that it aims to apply design and creative techniques to support the UK’s industrial strategy. The ultimate objective is to further grow and scale up the North West cluster of creative industries while strengthening and contributing to the broader industry. For this, students must collaborate on projects with large or small corporations.

A variety of themes were presented to the cohort:

- Technologies for the creative industries
- Transformative digital technologies
- Manufacturing processes and materials of the future
- Bioscience and biotechnology
- Leading edge healthcare and medicine
- Smart, flexible and clean energy technologies
- Quantum technologies
- Robotics and artificial intelligence
- Satellites and space technologies

The first theme listed above, “Technologies for the Creative Industries”, has been substantial to this research, as the projects established here can provide new concepts for the development of spatial sound and lighting technology.

In order to approach industrial collaboration, several companies were contacted. The initial goal was to find collaboration for the development of music technology; however, the North West region does not present a visible audio industry. Thus, an alternative strategy was to collaborate with companies working with other technology that could be relevant to the inquiries and portfolio presented here.

Two projects were developed through the Transformation North West programme: *AudioTrek* and *OPPO*. The *AudioTrek* project (Appendix, 9.1.1) was developed alongside Pulse Systems, a start-up company based at Sensor City business hub in Liverpool. The company’s specialisation is in electronics manufacturing, and this provided skills and guidance to the research which were valuable for further projects (see Chapter 6). Similarly, the *OPPO* project (Appendix, 9.1.2) cooperated with Sensor City and progressed to a collaboration with the Sidney Jones and Harold Cohen libraries at the University of Liverpool. These institutions provided spaces for data collection and building information, which were primarily relevant for another member of the Transformation North West researching the use of data in architecture, but also produced knowledge on tools and methods for interpreting building data through music technology.

Finally, a strategy that enabled engagement in the region utilising music technology was through the creation of a new limited company, Sonalux, based in Liverpool. The projects presented here inspired new design ideas and the commercialisation of products for musicians. This is further explained in the conclusion chapter (Chapter 6).

3.3 Research Tools and Training

For creating music, software for music notation (e.g., Finale) and audio production (e.g., Pro Tools and Reaper) were utilised, alongside software for creating interactive tools for performance, such as Cycling '74's Max and Capture.

Concerning the production of prototyping devices and hardware, the Arduino IDE platform was particularly useful as open-source libraries are widely distributed for its programming language, facilitating the integration of a range of technologies (e.g., sensor, light and sound module control). The microcontroller units utilised during the research include: ATmega328p (*Syntony*, 5.1; *Sound Canvas*, 5.7; *PlatFORM*, 5.8), ATmega32u4 (*Future Lights*, 5.5; *Intersidereal*, 5.6; *Sound Canvas*, 5.7), ATtiny84 (*Immanence*, 5.3), OpenMV Cam M7 (*AudioTrek*, 9.1.1), JeVois (*AudioTrek*, 9.1.1), ESP-WROOM-32 (*Immanence*, 5.3; *Sound Canvas*, 5.7; *OPPO*, 9.1.2), Teensy 3x and 4x (*Sound Canvas*, 5.7).

For the design of circuit boards, Autodesk's EAGLE was utilised. EAGLE is an electronic design automation (EDA) software, allowing the design of schematics and printed circuit boards (PCBs) (Autodesk, n.d). The exported design files can be sent to PCB fabricators for production. Once the boards are fabricated, components can be assembled for completing the circuit boards.

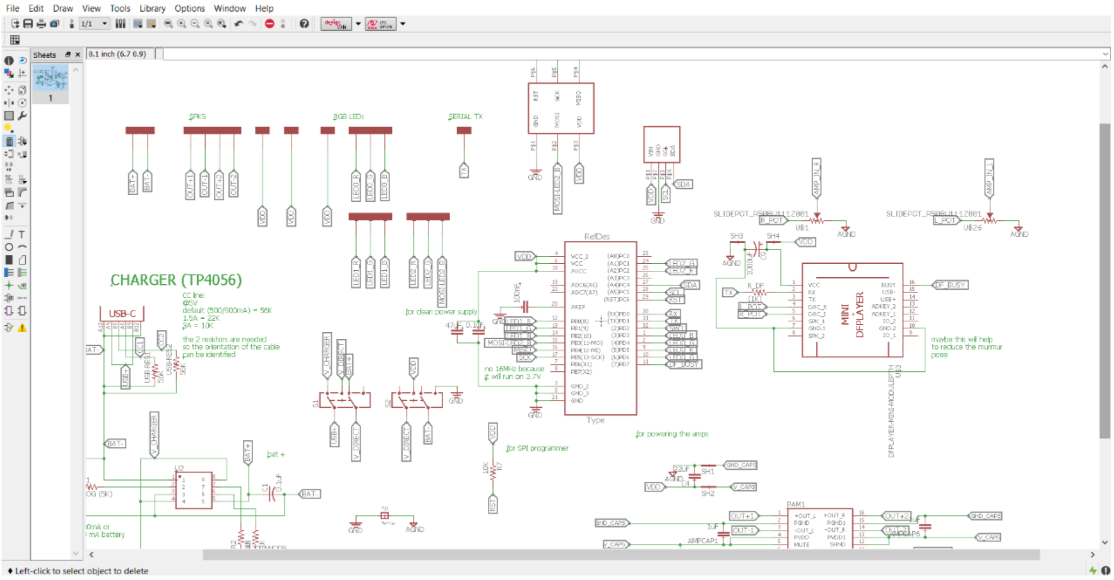


Figure 1. Eagle screenshot: Schematic utilised in the Sound Canvas project.

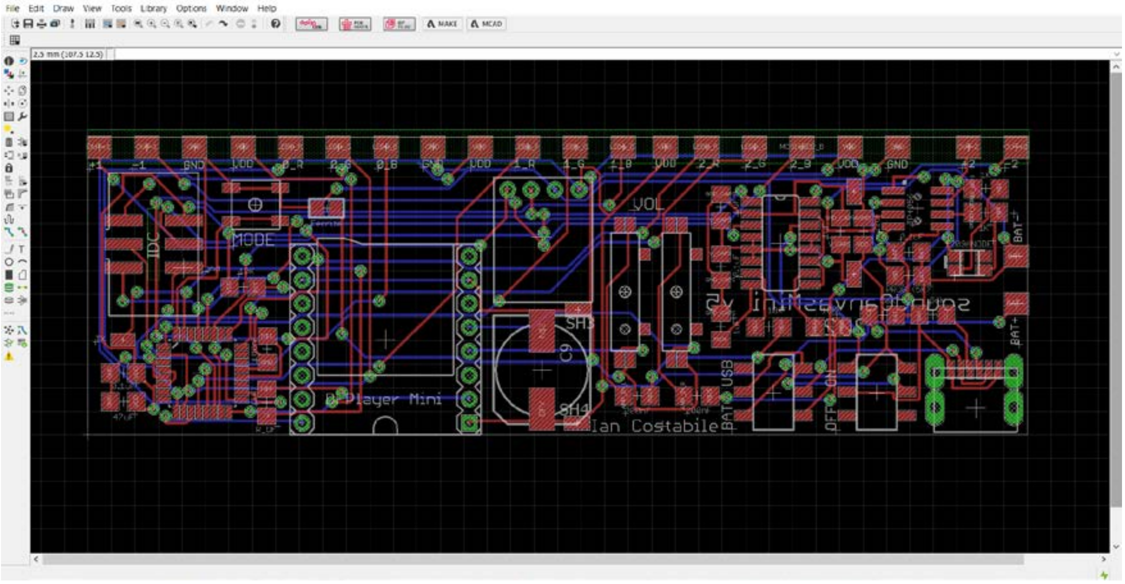


Figure 2. Eagle screenshot: Circuit board design utilised in the Sound Canvas project.

In order to gain knowledge in electronics manufacturing and skills for applying soldering techniques, the following training was provided by The Electronics Group Training Centre in Leeds:

- Introduction to hand soldering surface mount components training course.
- Advanced hand soldering and reworking of surface mount components training course.
- IPC 610 (Rev G) CIS training course.

Considering the enclosures developed for prototypes, 3D design and printing software such as SketchUp and Cura were also effective tools for this research.

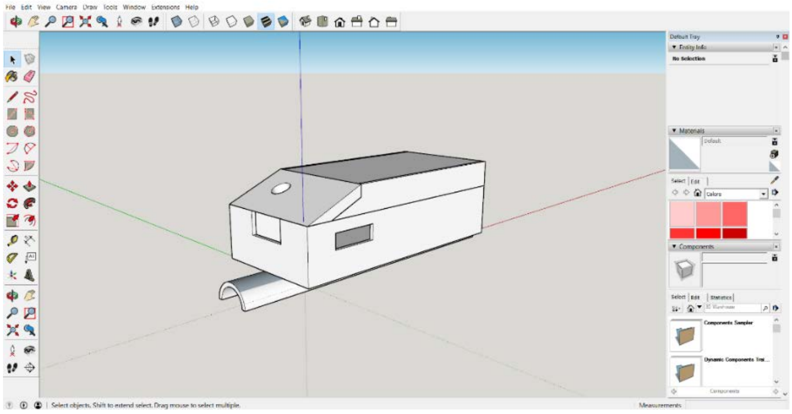


Figure 3. Sketchup screenshot: Enclosure for Device #1 to be attached to string bows in Immanence (5.3).

3.4 Performances and Exhibitions

Compositions were performed at:

- University of Liverpool Lunchtime Concert Series (Live Stream) April 2021: Intersidereal
- Independent Online Performance, September 2020 (Live Stream): Future Lights
- Open Circuit Festival, November 2019: Immanence
  Bridewell Studios & Gallery, June 2017: Syntony
- Pisa Baptistery, Italy, April 2017: Voci della Terra e del Cielo
- Open Circuit Festival, March 2017: Bi-Dimensional

Installations were exhibited at:

- Sensor City, 2019: OPPO
- Tate Liverpool, 2018: PlatFORM
- Threshold Festival, 2017: Sound Canvas

4 Interacting with Space and Light

This chapter introduces basic notions of sound spatialisation and lighting for compositional use. In order to develop interaction between sound and these two mediums, the use of interfaces—i.e., platforms that allow systems to interact—is required. Therefore, an overview of the basic requirements for the design of spatialisation and sound-light interfaces is presented.

4.1 Fundamentals of Spatialisation Interfaces

Throughout the development of the research projects presented here—in particular, the *Sound Canvas* project (5.7)—an understanding of interfaces for spatial projection was essential. Experimental interfaces were developed through Max (see *Lyra Multichannel Player* in 9.3) and through custom-made circuit boards (see 6.3). Four basic elements that were found to be substantial in the design of spatialisation interfaces are presented in this section: operational mode, projection type, loop function and spatialisation techniques.

4.1.1 Operational Mode

A system can be manually operated, or it can be automated. An operator can control a keyboard, knobs or switches for changing the projection space. It is also possible for performers to take control, as in *Bi-dimensional* (controlled by pitch; 0) and *Syntony* (controlled by distance sensors; 5.1).

For an automated system, projection events can be recorded and played back. A basic automatic setup might consist of a time indicator (BPM or milliseconds) to switch between channels with regularity, a panning law selector, and the trajectory order the channels should follow. A common example is an ‘Autopan effect’, which is widely available in the form of audio plugins for digital audio workstations. The work *Sound Lines #1* produced through the *Sound Canvas* project (5.7) utilised a microcontroller program that shifted sound material between two speakers within a constant and regular time set to 31.8 BPM—this number was important to accurately represent the work’s concept, which was inspired by the Earth’s rotation around the Sun.

4.1.2 Projection Type

The engineer Jacques Poullin who worked in a spatialisation device with Pierre Schaeffer in the 1950s (see 2.1) described two possibilities for sound projection: ‘static relief’ and ‘kinematic relief’ (Harley, 1994). The French term *relief* refers to the idea of a ‘landscape’, or a spatial image.

The concept of ‘static relief’ asserts that sounds can be spatialised in a fixed space, without presenting motion between loudspeakers. The installation *PlatFORM* (5.8) exemplifies this concept, as it presented multiple speakers emitting individual sounds without creating any form of kinetic interaction. As for the concept of ‘kinematic relief’, this defines that spatialised sounds are manipulated to generate kinetic motion and trajectories from one loudspeaker to another. This form of projection was the main approach throughout the Sound Canvas project (5.7).

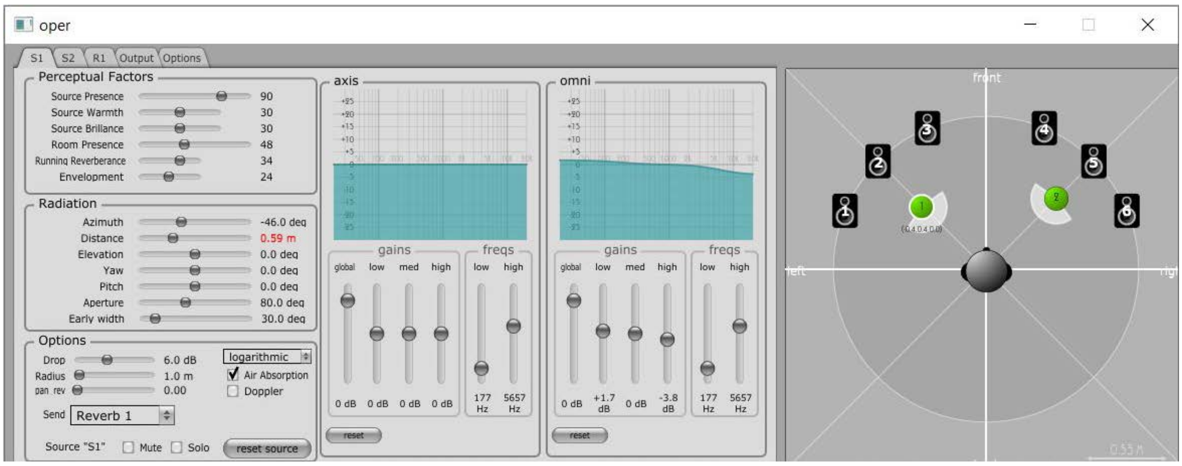
4.1.3 Loop Function

A basic function that might be required is a ‘loop function’. It may be important that a composition (or spatialisation effect) will repeat during a performance. For instance, all sound canvasses (5.7) produced in this research required a loop function active from the moment the works were switched on, so they could run continuously for several hours throughout an exhibition. In some cases, the sound material might not be prepared to be looped, as when the onset and offset are different. This can produce undesired audio clicking or abrupt changes in volume. To avoid this, sounds can be edited with fades to allow gapless playback or seamless loops. It is also important to note that MP3 encoding creates a gap at the beginning and end of the audio. If MP3 files are essential, such as when using the DFPlayer module (DFRobot, n.d.), one solution is to edit the audio to be duplicated with several seamless loops. This method was utilised for the *PlatFORM* installation (5.8), where the length of audio files was over 5 hours. This way, a small sound gap might still be perceived; however, it will occur within a long period, not compromising the audience’s experience.

4.1.4 Spatialisation Techniques

A variety of spatialisation techniques and algorithms exist, such as amplitude panning, which is the most basic technique, and others, such as vector base amplitude panning (VBAP), Ambisonics and Wave Field Synthesis (WFS) (Roads, 2015, pp. 275—282). They present different ways of distributing sound to two or more loudspeakers.

Two performance projects presented in this research explored spatialisation techniques with virtual sources: *Bi-dimensional* (0) and *Syntony* (5.1). *Bi-dimensional* utilised a six-speaker setup positioned in the shape of an arc layout behind the audience. This spatial configuration was set by using Cycling '74’s Max with IRCAM’S Spat 4, an external Max package for sound spatialisation (IRCAM, n.d.). This package allows a virtual simulation of the speaker layout and provides the necessary calculations for a variety of panning techniques. It also provides perceptual factors such as room reverberance and control of the source's aperture. The Spat technique chosen for *Bi-dimensional* and *Syntony* was "angular", which is equal to amplitude panning speaker pairing with a constant power panning law (see 4.3 for further clarification).



Perceptual Factors
Source Presence 90
Source Warmth 30
Source Brillance 30
Room Presence 48
Running Reverberance 34
Envelopment 24

Radiation
Azimuth -46.0 deg
Distance 0.59 m
Elevation 0.0 deg
Yaw 0.0 deg
Pitch 0.0 deg
Aperture 80.0 deg
Early width 30.0 deg

Options
Drop 6.0 dB
Radius 1.0 m
pan rev 0.00
logarithmic
☑ Air Absorption
☐ Doppler
Send Reverb 1
Source "S1" ☐ Mute ☐ Solo

axis
gains: global 0 dB, low 0 dB, med 0 dB, high 0 dB
freqs: low 177 Hz, high 5657 Hz

omni
gains: global 0 dB, low +1.7 dB, med 0 dB, high -3.8 dB
freqs: low 177 Hz, high 5657 Hz

Figure 4. *Spat.oper* object in Spat for Max, screenshot showing the distribution of two sources between six speakers.

Attention to techniques of spatial sound in this research came mainly from the *Sound Canvas* project (5.7), which aimed to produce a variety of artworks with loudspeakers and compact multichannel circuitry, operated mainly by microcontrollers. This project specifically focused on 2-D setups, meaning all loudspeakers were in the same plane as the listener. This excluded the need for surround and complex techniques and allowed basic amplitude panning approaches to be explored.

Describing in further details the different spatialisation techniques is beyond the scope of this research (see Pulkki, 2001, p.11–19, for more details), however, the foundations of amplitude panning is presented in section 4.3, alongside studies developed for the Sound Canvas project.

4.2 Designing Sounds for Spatialisation

Sound localisation studies are significant for defining 'good' spatial materials, which can be more accurately perceived and thus support spatialisation. Considering whether the material will be continuous or pulsed (including variations in rhythm or melody) will also determine localisation accuracy. Therefore, it is fundamental to analyse and select the most appropriate compositional materials for efficient spatialisation.

4.2.1 Localisation and Continuity

For projection works employing the principle of *kinematic relief*, continuous sounds should be preferred, as this will allow the 'same' sound object to be perceived when shifting from one speaker to another, creating a better kinetic effect and the illusion of something material moving in space—this can be illustrated by a mosquito buzzing in the air, which reveals its trajectory through sound. However, for projections working mainly with *static relief*, non-continuous or rhythmic sounds may provide more auditory information and facilitate the localisation of sources, as studies have shown that pulsed noise is less difficult to localise than continuous noise (Risoud et al., 2020).

4.2.2 Localisation and Frequency

Studies have shown that frequencies between approximately 2 kHz and 4 kHz do not provide reliable horizontal localisation cues (Middlebrooks, 2015, p. 101). Therefore, avoiding this region when selecting material can be beneficial for spatialisation. In consideration to vertical localisation, sounds can be more accurately located if they include 7 kHz components (Risoud et al., 2018).

It is well known that white noise allows better localisation than pure tones (Stevens and Newman, 1936; McCarthy and Olsen, 2017), as it has been observed:

> Noises in general have both high and low frequencies present. The low frequencies provide sufficient phase-differences and the high frequencies sufficient intensitive differences for localization. The two types of cue render each other mutual support, and the result is an accuracy of localization greater than that obtainable with pure tones. (Stevens and Newman, 1936)

Richer spectrums, in general, will allow better localisation. For both horizontal and vertical directions, sounds with a broad spectrum of frequencies will provide more localisation cues than sounds with narrow bands (Risoud et al., 2018).

4.2.3 Design Methods

For the compositional portfolio produced in this research, several sounds were designed with the recommendations suggested above in order to provide efficient localisation. For sound selection, a sound library was created that was organised by type of continuity (looped or stretched), frequency range, and other properties (such as spectrum density). These were initially made through digital synthesisers and a variety of synthesis algorithms (e.g., additive synthesis, see *Spectrum Designer* in 9.2) to operate in specific frequency ranges, and post-processed to become continuous through seamless loops or ‘stretched’ sounds.

A Max patch was developed for converting sound samples into seamless loops, which can be done by looping a sound section and defining a crossfade between the onset and outset. For optimal results, the crossfade must follow a sinusoidal or square-root curve, which allows listeners to perceive the intensity change more naturally (this phenomenon is further explained in 4.3). In addition, an automatic amplitude panning (autopan) Max patch was also designed for the creation of spatialised stereo sounds (see Figure 5).

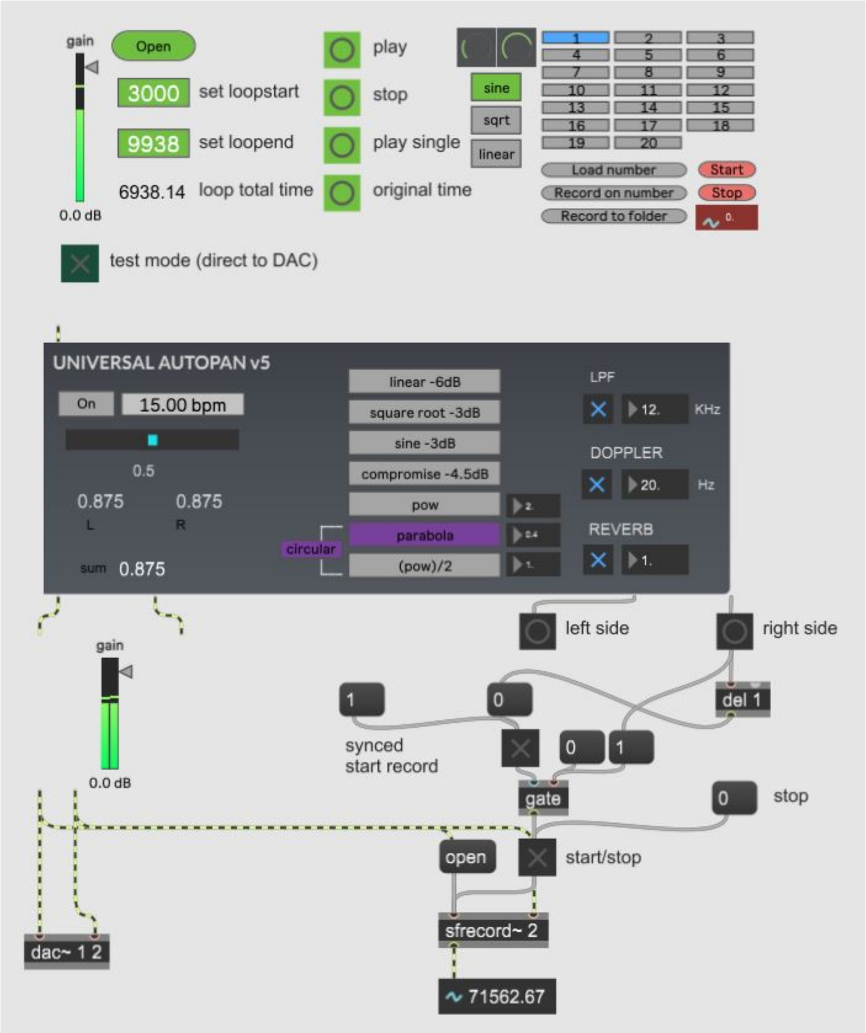


Figure 5. Max patch for sound design, including a seamless looper and autopan.

Sounds can also become continuous by utilising granular synthesis techniques, which consist of manipulating very short pieces (grains) of a sound sample (see Roads, 2001) The open-source software Paul's Extreme Sound Stretch was used for generating sounds through a similar method (Nasca, n.d.a; Nasca, n.d.b). In this program, users can load a sound file, identify the region, a final length and then generate a new ‘stretched’ sound file.

4.3 Amplitude Panning Studies

The *Sound Canvas* project (5.7) required further investigations on amplitude panning. This method can be efficient for two-dimensional panning—i.e., where all loudspeakers are in the same plane as the listener, contrary to surround techniques—and can be easy to implement in microcontroller codes.

Linear Panning Law

The most basic amplitude panning takes a linear function. Consider, for example, that we are projecting a sound in two loudspeakers, and we aim to create spatial motion from the left to the right speaker. This can be achieved by beginning with 100% of sound volume in the left speaker and 0% of sound in the right speaker, and while the signal is panned to the right the power levels are proportionally inverted. As one channel is attenuated and the other fades up, this creates the panning motion effect. In the most basic audio setup, the power levels will change in a linear scale (the centre point will be 0.5).

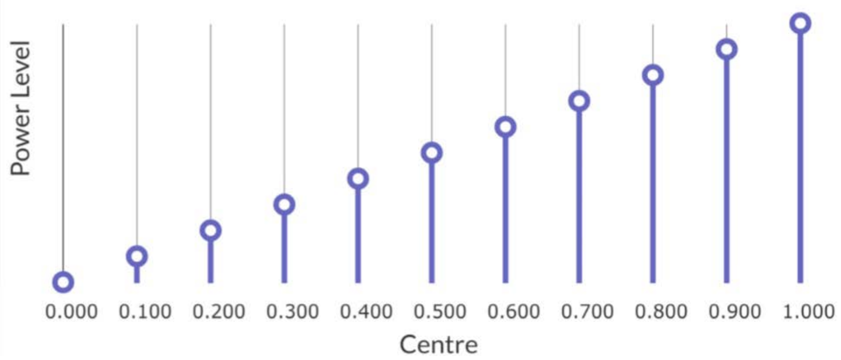


Figure 6. Function of the Linear Panning Law.

However, it is important to note that this will create a 'hole in the middle', as sound intensity will be perceived as decreasing in the centre (Roads, 1996). This happens because the way humans perceive loudness is not proportional to acoustic power. When we distribute a sound between two loudspeakers with half of the total volume, 50% in one speaker and 50% in the other, the perceived sound does *not* add to 100% in loudness. As it has been acknowledged: 'Doubling power from 1 to 2 watts is a 3-dB increase in power level (10 log 2 = 3.01), a very small increase in loudness.' (Everest, 2001, p.31). A solution to avoid this level decrease in the centre is to use a constant power panning law, which is explained in the next section.

Constant Power Panning Laws

By using square root or sine functions, panning can be created with more stable loudness. The square root calculation can be applied to the panning values which generates a function where 0.707 becomes the central value.

Square Root Panning Law:

rightAmp = √x
leftAmp = √(1-x)

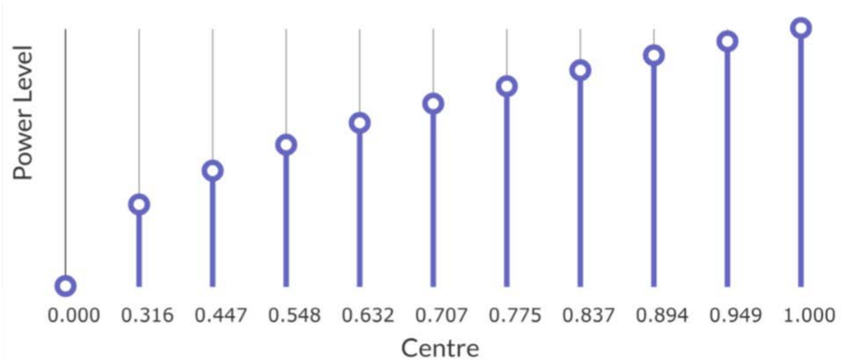


Figure 7. Function of the Square Root Panning Law.

Better results can be achieved by using a sine function known as Sine Panning Law (or Cosine Panning Law) (Creasey, 2017; Farnell, 2010). The central value is again 0.707, but the curve is greater on the sides.

Sine Panning Law:

rightAmp = sin(x*pi/2)
leftAmp = sin((1-x)*pi/2)

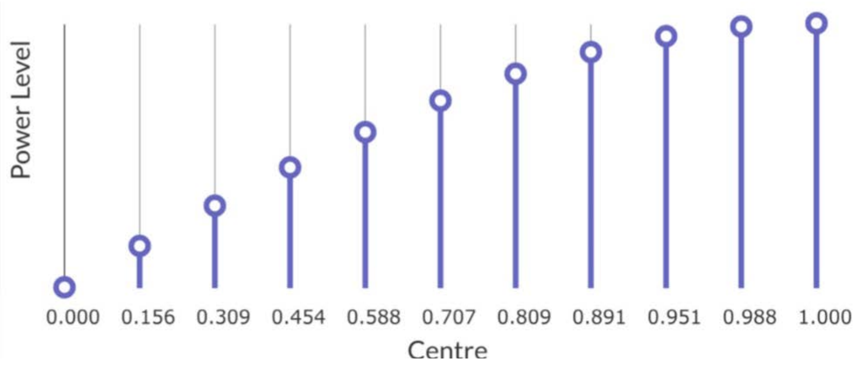


Figure 8. Function of the Sine Panning Law.

Other Panning Laws and Distance Effects

Other functions can be used for generating a variety of panning effects. Experiments in this research have shown that by utilising a power function, distance can be simulated. As it happens with the linear panning law, a 'hole' can be created in the centre. It is important to add that, besides the decrease in amplitude, other effects can be added for a more improved 'illusion' of distance, such as a lowpass filter, echoes or reverberation (see Roads, 1996, p.462).

Power of Two Panning Law

Raising an exponential to the power of 2 will create further decay in the centre.

$$\text{rightAmp} = x^2$$
$$\text{leftAmp} = (1\text{-}x)^2$$

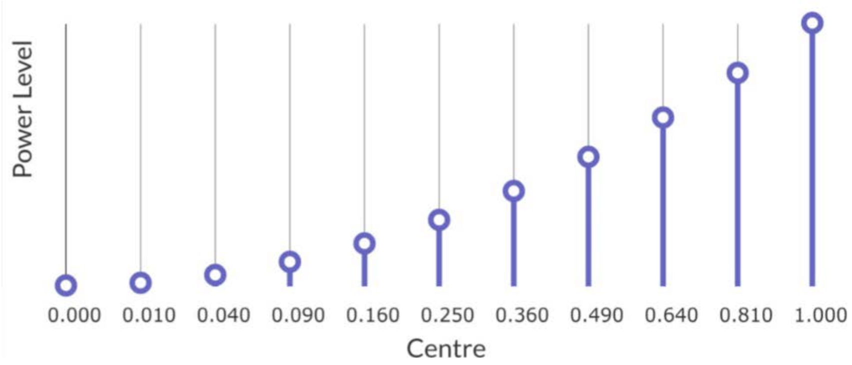


Figure 9. Function of a Power of Two Panning Law.

Increased Gain Panning Law (Parabola)

Other experiments produced in this research have shown that the opposite effect, where sound in the centre appears to be louder, is also possible. For this, it is necessary to consider that the previous panning calculations followed a single ramp (0. to 1). One way of creating a panning effect where the centre is louder is by making the crossfade increase and decrease.

For instance, a function could start at 0., reach the centre at 1., and end at 0.5. This can be created with a parabola equation: $f(x)=3.5x - 3x^2$. However, this equation raises values near the centre to 1.021, which can cause clipping. To avoid this, a more moderate parabola equation can be considered: $f(x)=3.4x - 2.9x^2$. This way the function's maximum value is 0.996.

$$\text{rightAmp} = 3.4x - 2.9x^2$$

$$\text{leftAmp} = 3.4(1\text{-}x) - 2.9(1\text{-}x)^2$$

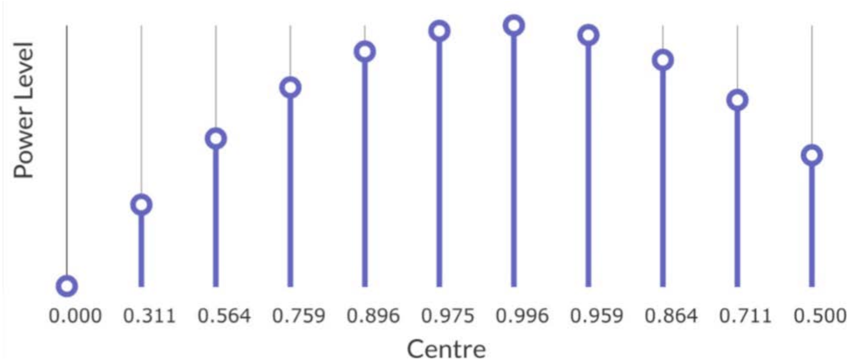


Figure 10. Function of a Parabola Panning Law ($f(x)=3.4x - 2.9x^2$)

Circular Depth Study

During the *Sound Canvas* experiments (5.7), one of the goals was to obtain an effect that could simulate a spatial projection approaching and distancing from the listeners, creating a circular depth motion. One method found through the simple use of gain panning was to create an interchange of the power of two function (i.e., decreasing gain) with a parabola function (i.e., increasing gain). The power of two calculation must be divided by 2 to result in a total range of 0. to 0.5, thus both functions maintain the same levels and the sound trajectory can be continuous.

The parabola function can also be adjusted for better balance. This can be done by changing the z value of the equation: $f(x)=(3.4x - z) - (2.9 - z)x^2$. A value of 0.4 (or: $f(x)=3x - 2.5x^2$) seemed to provide reasonable results.

In this method, the sound first appears to move closer to the listener, and as it continues the next panning round it appears to distance from the listener, like a rotating circle. The illusion is better supported by added reverberation and filters. This effect was presented in a few sound canvasses, such as *Collage #2* and *Pulsar* (5.7).

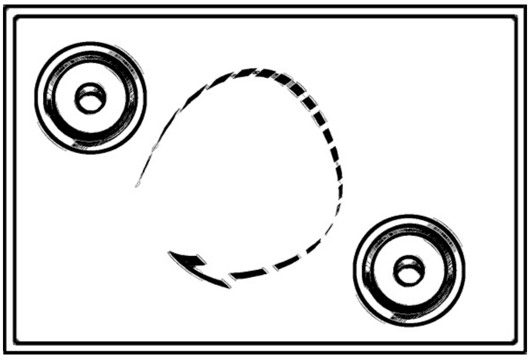


Figure 11. The circular depth effect is explored in the sound canvas *Pulsar* (2017).

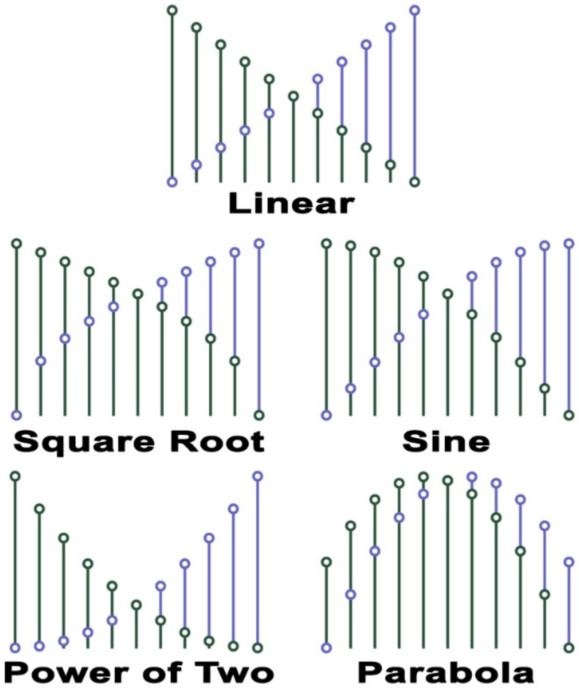


Figure 12. Comparison of possible panning law crossfades.

4.4 Fundamentals of Sound-Light Interfaces

When working with light instruments that interact with music there are some fundamental considerations to be taken. In this section, we analyse two aspects: mapping types and mapping methods.

4.4.1 Mapping Parameters

As music is constituted by a variety of formal elements—e.g., pitch, rhythm, harmony—and lighting has also its properties—e.g., brightness, strobe, direction—multiple combinations can be created. *Table 1* compares a list of elements that can be exchanged.

Music	Lighting
Frequency / Pitch / Melody	
Spectrum / Waveform	Brightness (Dimmer)
Harmony / Chords / Tonality	Colour
Rhythm / Note Duration	Shutter (Strobe)
Tempo	Position
Dynamics / Intensity / Amplitude	Beam Size (Zoom)
Timbre / Orchestration / Texture	Beam Angle (Pan/Tilt)
Spatial Position	Beam Speed
Spatial Kinetic Direction	Gobo (Shape)
Spatial Kinetic Speed	Number of Light Instruments
Form / Music Sections	Scenes
Techniques (e.g., tremolo)	Laser Drawings
Signal Processing Effects (e.g., echo)	

Table 1. Elements of music and lighting that can be exchanged.

In concerts, lighting designers will often study a music piece and find possible links to be added to the cue sheet. Typically, music sections (or acts/performances) receive different lighting scenes. Designating a lighting scene to specific musical moments is an effective technique for creating contrast and expressing conceptual ideas.

Particularly, in rock and electronic music concerts, intensity, rhythm and tempo are often plotted for manual control of brightness and beam angles. Sound spectrum mapping to brightness or colour is another common effect, which can be seen as a feature of light organ machines, popular in nightclubs since the 1970s. *Table 2* presents the three most common sound to light interactions.

Sound Input	Light Output
Music Sections/Pieces	Lighting Scenes
Intensity / Rhythm / Tempo	Brightness / Beam Angle
Sound Spectrum	Brightness / Colours

Table 2. Common sound-light mapping parameters.

There are a few reasons to consider why other interactions are not explored. Firstly, as many light designers are not able to read music, many musical parameters—such as melody—are often disregarded. For this reason, in classical performances and operas, reading music can be an advantage (Dunham, 2016, p. 295). Secondly, some parameters are not possible by manual operation, requiring automation specific equipment or digital programming skills. The third consideration is the overuse of interaction; light is usually accompanying music as a secondary art form and adding focus to lights might affect the original concept.

Table 3 shows the mapping combinations achieved through the portfolio presented in this research.

Sound Input	Light Output	Composition
Pitch	Brightness	Bi-Dimensional, Future Lights
Pitch	Beam Motion Direction	Future Lights
Pitch	Position	Bi-Dimensional, Intersidereal (Lyra)
Spatial Position	Position	Bi-Dimensional
Frequency Spectrum	Brightness	Future Lights
Waveform	Laser Drawings	Organoids
Harmony	Colour	Intersidereal (Nebulae)
Intensity	Motion	Future Lights
Intensity	Brightness	Immanence, Intersidereal (Celestial)
Dynamics	Brightness	Future Lights
Tremolo	Strobe	Future Lights
Tempo	Brightness	Intersidereal (Minuet of Stars)
Echo	Brightness	Intersidereal (Light Echoes)
Echo	Position	Intersidereal (Light Echoes)

Table 3. Sound-light mapping found in the portfolio.

4.4.2 Mapping Methods

This research has identified four methods for interpreting sound to light:

1) Sensor-based automation (e.g., microphone, camera, motion).
2) MIDI instrument.
3) Automated operation score-follower.
4) Manual operation score-follower.

Sensor-based automation

The first method takes as input an electrical signal and converts it to data that can be utilised for lighting control. The electrical signal can be in the form of sound, as when captured by a microphone or instrument pickup, or by any other sensor that can react to an instrument control. For instance, the prepared mallets utilised in *Immanence* (5.3) included a piezo sensor, which converted the mallet's striking vibrations to signals that operated LED lights. If connected to an interface, the mallets could operate any type of controllable light on stage. There are many other types of sensors that can be used for tracking a performer's motion, including cameras coupled with computer vision technology for taking visual cues (e.g., a piano gesture tracking via camera can be seen in Ritter et al., 2013).

Common sound-light interaction through audio signals includes amplitude, pitch and spectrum tracking. These three translations were explored in *Future Lights* (5.5) by converting a microphone cello signal through a Cycling '74's Max patch. For amplitude, the Max object *peakamp*~, which tracks the signal's amplitude peaks in a certain interval of time, was implemented. Further settings for making the data logarithmic and therefore more dynamic can be seen on Tutorial 28 from the Max documentation (Cycling '74, n.d.b.).

Pitch tracking from an alto flute was automated in *Bi-dimensional* with the object *fzero*~ and it did not present any issues. For *Future Lights*, the external object *fiddle*~ (Puckette et al., 1998) was chosen. There are many other objects for Max that can also translate frequency to pitch (e.g., *retune*~ and *sigmund*~), but *fiddle*~ proved to be sufficient for this composition. Like many other algorithms that convert audio signals to the frequency domain, it fails to detect low frequencies, thus a footswitch for deactivating the pitch tracker at specific moments was notated in the score.

Tracking the spectrum of an audio signal is made through a spectrum analyser. It is implemented in most consumer electronics with “sound reactive” functions, such as DMX512 lights with in-built microphones or controllable LED strips. Since the early 1980s it has also been a common display function of HiFi Stereo Graphic Equalisers; e.g., Pioneer SG-50 and Technics SH-8055 (hifiengine, n.d.a; hifiengine, n.d.b). In Future Lights, this was achieved by utilising the *fffb~* object in Max, which combines individual bandpass filters to isolate the frequency bands. In the *Sound Canvas* project (5.7), some experiments with spectrum analyser were made by utilising a MSGEQ7 chip, which can separate the audio spectrum into seven frequency bands (MSI, 2004).

MIDI instrument

The MIDI protocol interprets sound through data. MIDI instruments that take direct mechanical input create precise data which can be integrated into a sound-light interface. However, MIDI interfaces that convert an analogue signal to MIDI operate as the first method present (sensor-based automation) and may be susceptible to inaccuracy. This approach is not presented through the portfolio produced, but it was tested with MIDI keyboards, providing excellent results for lighting control.

Automated operation score follower

It is possible to create automated light cues that will accompany a score in real-time. Score following techniques have been extensively studied by the IRCAM (Cont et. al., 2004) resulting in a program called Antescofo, which can be integrated into Max and PureData (IRCAM, n.d.). Antescofo analyses audio input and compares it with a score, in order to trigger pre-programmed electronic actions. The use of Antescofo can be extended to follow a score not only according to pitch detection but also with gesture tracking (see Ritter et al., 2013).

The score following method can be complex to adapt to certain compositions and is still prone to errors during performance. Therefore, this approach was not tested during this research.

Manual operation score-follower

An operator can follow the score during live performance and trigger cues manually through a lighting interface—e.g., DMX controllers. This approach was used for the performance of *Intersidereal* (5.6), where the operator read lighting cues notated on the score. This approach can facilitate the interaction between light and music performer; however, it might not be fast enough for all types of sound-light interaction—e.g., accompanying dynamics or sound spectrum—and might require the operator to be able to read music.

Manual operation can also be independent of interfaces. Portable lights (e.g., battery-operated torches) can be used by performers. A performance of this type can be seen in the film *Adolphe Appia, Visionary of Invisible* (1988). It presents the piece *La Villete*, by the composer Jean-Marc Aeschimann, in which eurhythmics[3] artists create light behind curtains in synchrony with the recorded music.

This chapter has demonstrated key aspects of spatial sound and lighting interfaces identified through this research. These aspects can be further developed and used as a reference for composition.

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[3] Dalcroze eurhythmics is a method for learning and experiencing music through movement (Mark and Madura, 2014, p.100).

5 Portfolio

Title	Instrumentation	Duration	Media	Credits
		PART I - SPATIAL COMPOSITIONS		
Syntony	Cello, Electronics and Live Painting. 2 channels.	c. 15’ (score) (18’ video)	• Score (PDF) • Video[4] (syntony.mp4) • Source Code	David Gomez (cello) and Jakub Kreft (visual artist), Bridewell Studios & Gallery, June 2017.
Bi-dimensional	Alto Flute and Electronics. 6 channels.	c. 7’	• Score (PDF) • Video[4] (bidimensional.mp4) • Source Code	Richard Craig (alto flute), Open Circuit Festival, March 2017.
		PART II - SOUND-LIGHT COMPOSITIONS		
Immanence	Percussion Trio and Augmented Instruments.	c. 10’	• Score (PDF) • Video (immanence.mp4) • Source Code	Line Upon Line, Open Circuit Festival, November 2019.
Organoids	Bass flute, Baritone Saxophone, Cello and Light Projection.	c. 5’	• Score (PDF) • Video (organoids.mp4)	Riot Ensemble, July 2021, PRiSM 8[3].
Future Lights	Cello and Light Projection.	c. 10’	• Score (PDF) • Video (futurelights.mp4) • Source Code	Georgina Aasgaard (cello)
Intersidereal	Harp and Light Projection.	c. 15’	• Score (PDF) • Video (int_1_lyra.mp4, int_2_nebulae.mp4, int_3_minuet.mp4, int_4_light.mp4, int_5_celestial.mp4) • Source Code	Bethan Griffiths (harp), Lunchtime Concert Series UoL
		PART III - GALLERY WORKS AND INSTALLATIONS		
Belt of Orion	Sound Canvas media. 3 channels.	c. 2’30”	• Video[4] (SC_Belt.mp4)	
Pulsar	Sound Canvas media. 2 channels.	c. 2’	• Video[4] (SC_Pulsar.mp4)	
Sound Lines #2	Sound Canvas media. 4 channels.	c. 1’	• Video[4] (SC_SLines2.mp4)	
PlatFORM	Installation. 40 channels.	15’ (7’ video)	• Video (platform.mp4)	Eduardo Coutinho, ECAlab, Tate Liverpool

Table 4. List of Selected Works and Accompanying Media

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[4] Stereo audio recorded with binaural microphone (Roland CS-10EM) or similar technique.

PART I - Spatial Compositions

5.1 Syntony

5.1.1 Concept

Syntony was composed for cello, live electronics, and live painting interaction. An interactive system of motion to sound was designed in a way that the painter's motion around the canvas was tracked and mapped to modify the cello's sound, along with the spatialisation around the audience.

The title, *Syntony*, refers to the syntonic state of being responsive to the environment. This corresponds to the painter's actions and judgment by hearing sound changes, and the same applies to the cellist's execution while seeing the painting's transformation. Thus, the two performers are influenced by each other, mutually developing the composition.

5.1.2 Objectives

1. To design a system for tracking the painter's motion.
2. To control stereo sound spatialisation through motion.
3. To explore sustained sonorities for the cello, allowing tracked changes from the painter's input to be better perceived.

5.1.3 Design

Four ultrasonic sensors HC-SR04 were attached to a wooden support bar, evenly spaced under a 160x120cm canvas (Figure 13). These sensors can measure distances from 2 to 400cm (Elecfreaks, n.d.) and were used here to track the position of the painter's hand. They were connected to an Arduino board (based on the ATmega328p microcontroller) and their values were transmitted via USB serial communication to Cycling '74's Max. A microphone was used to capture the cello's signal, to be processed in Max and outputted along with electronic sounds to two loudspeakers.

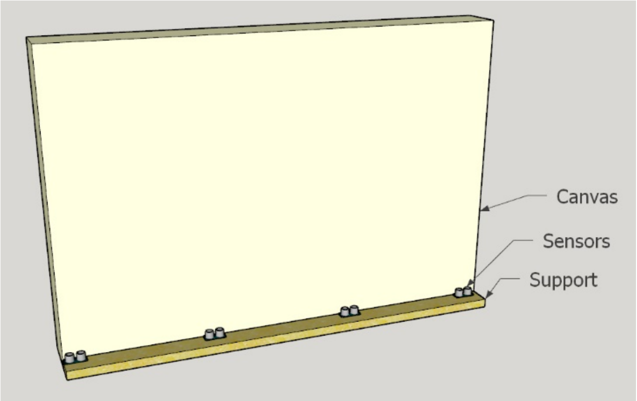

Figure 13. Prepared-canvas with four ultrasonic sensors.

Through Max, an interface for sensor reading and sound control was designed. Six samples pre-designed through synthesisers and other means were selected and made ready to be looped through Max’s *groove~* object. The effects list for altering the cello’s sound were pitch shifting (based on the *pitchshift~* object), a comb filter, flanging and reverb (the last three were directly integrated through Max’s native Beap modules and abstractions). Effects were assigned to different sections of the composition and their parameter levels changed according to the sensor’s data, or the height of the brush.

For stereo panning control, amplitude panning with a constant power law (see 4.3) was integrated into the Max patch. Through this method, the spatial motion between the two speakers could be perceived as having the same sound level throughout the panning trajectory. Four panning positions were linked to the four sensors, thus, for instance, if the painter’s hands moved from the left to the right corner of the canvas, the sound would appear to navigate from the left to the right speaker.

A Max presentation screen was designed for live operation, so the operator could control the musical changes according to the sections, calibrate the sensors and monitor the data and audio signal inputs during the performance.

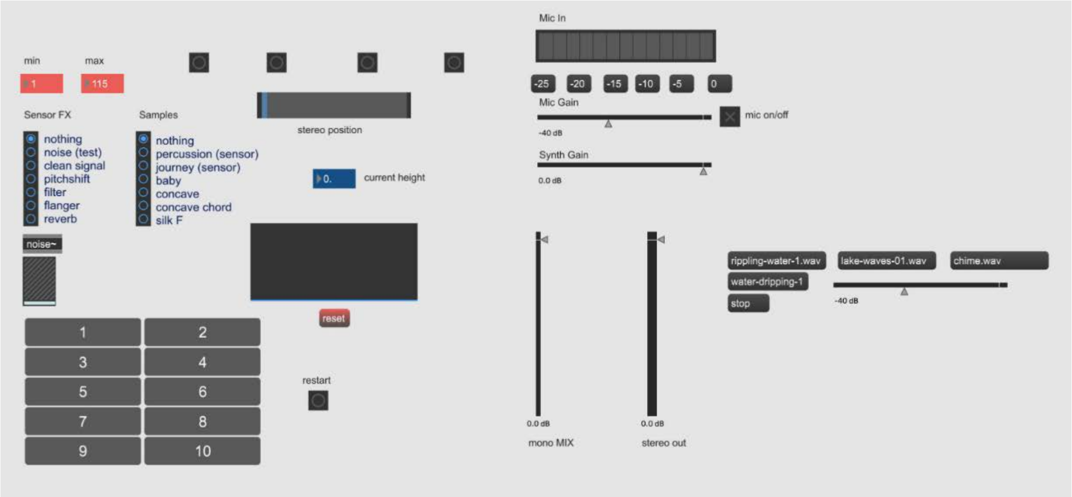

Figure 14. Syntony: Max patch in presentation mode.

5.1.4 Compositional Structure and Material

The composition is structured in 10 sections. Harmonic and melodic material selected was minimal since the aesthetic focus aimed to highlight the effects and spatial changes manipulated by the painter in action. Thus, timbral techniques to create a sense of *stasis*—i.e., continuous sounds (see 4.2.1)—were employed. All sections followed the same repetitive structure and examples of different explorations are shown below.

In Section 1, the cello sustains the note "F2" while the bow shifts from *sul tasto* to *sul ponticello* and vice-versa. After eight repetitions, the tempo moves through *accelerando* and *ritardando*. This pattern of tempo changes repeats throughout the piece. The electronic sound accompanies the cello with the note "F" in a higher octave. No modulation effect was assigned to the cello in this section.

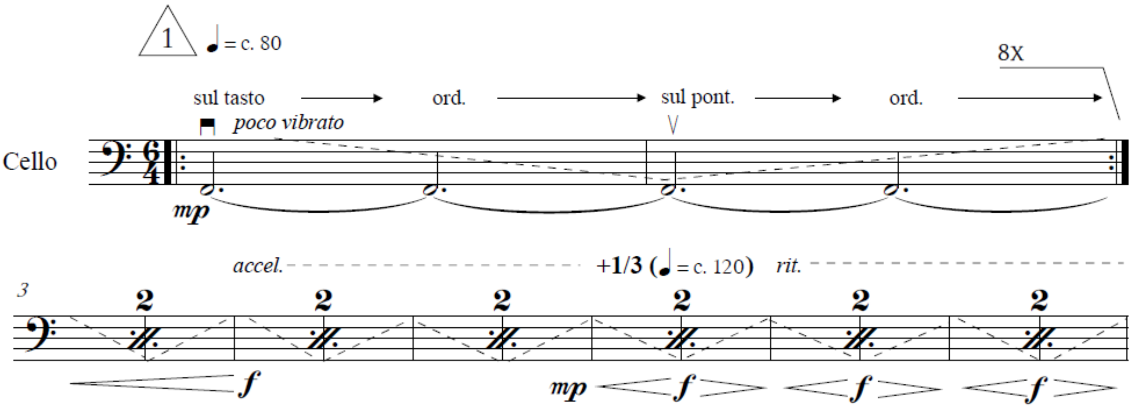

Figure 15. Syntony: Section 1.

In Section 2, the bow sustains direct contact with the bridge's wooden piece, not producing any pitched sounds. The assigned effect was comb filter.

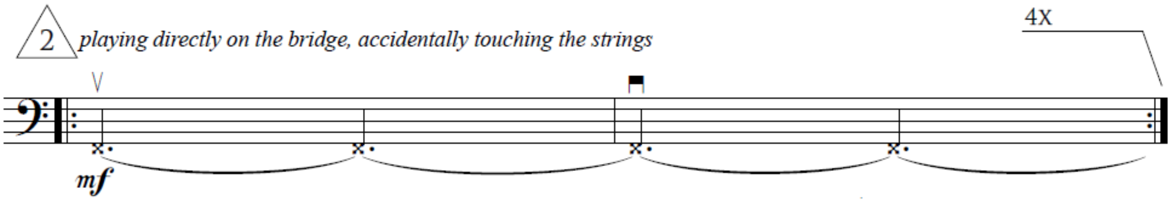

Figure 16. Syntony: Section 2.

In Section 5, harmonic tremolos were explored, and the assigned effect was flanging.

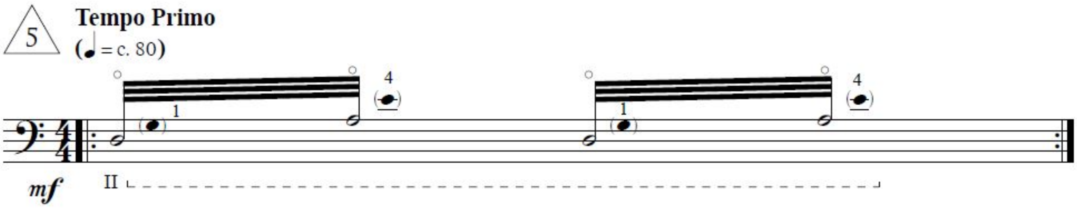

Figure 17. Syntony: Section 5.

In Section 7 the bow hits the higher strings with the wooden part (*col legno*), moving up and down the bout. The assigned effect was reverb.

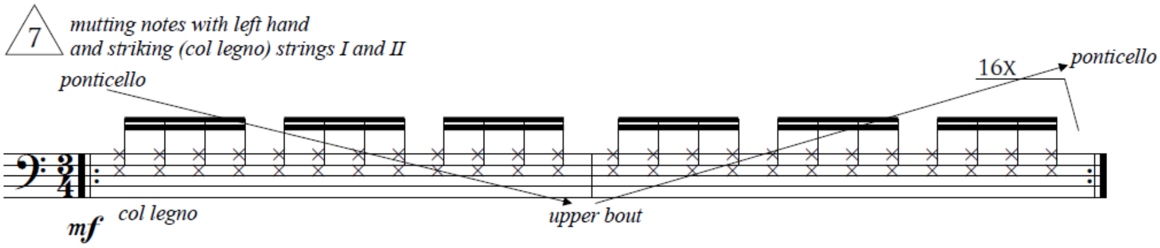

Figure 18. Syntony: Section 7.

5.1.5 Outcomes

Syntony was performed by David Gomez (cellist) and Jakub Kreft (visual artist) at Bridewell Studios & Gallery in Liverpool, UK, in June 2017. It was video recorded with two cameras. The spatialisation effect of following the painter's position was effectively synchronised, and the modulation changes created by tracking the brush's height seemed to be well pronounced.

Initially, the composition was prepared for 15 minutes plus the last section in *ad libitum*, as we expected the performance to last about 20 minutes. As the painter continued to work after 20 minutes, the cellist and sound operator began improvising with the material from previous sections. Finally, the performance was extended and resulted in about 35 minutes duration.

Figure 19. Syntony: Rehearsal and room setup.

Figure 20. Syntony: Performance.

5.2 Bi-dimensional

5.2.1 Concept

Bi-dimensional is a piece for alto flute, electronic sounds and light and space interaction. A system was designed using Cycling '74's Max to track pitch changes which were mapped to six illuminating loudspeakers around the audience. Therefore, the title suggests the interplay between two musical dimensions: the 'pitch space' and the 'auditory space'.

The length of the performance is approximately 10 minutes. This composition was performed at the Victoria Gallery & Museum in Liverpool at the Open Circuit Festival, in March 2017. It resulted in the production of an interactive and multichannel *sound canvas* (5.7) for gallery exhibition.

5.2.2 Objectives

1. To compose music for alto flute and spatial sound interaction through pitch and amplitude detection.
2. To design an interface for spatial sound and lights through Cycling '74's Max and the DMX protocol.
3. To explore the collaboration of spatial sound with lighting.
4. To take recordings from the performance and represent the same interactive approach through a mixed-media format (*sound canvas*) for gallery exhibition.

5.2.3 Design

The interaction system for performance was designed through Cycling '74's Max using IRCAM'S Spat 4, an external Max package for sound spatialisation (IRCAM, n.d.). Max connected to six DMX light units via a USB to DMX interface (Enttec). A footswitch MIDI board was provided for the performer to change section cues.

The performance was recorded with a 360 camera (Ricoh Theta S) along with a 4-channel surround recorder (Zoom H4n). The mixed-media project produced after performance integrated an Arduino board (using the ATmega32u4 chip) for switches and light control, and a PC stick running Max on Windows 10 for executing the recording and interaction control (via microphone input). In addition, this system was supported by a compact six-channel audio interface, one microphone, six LED lights and 3W speakers. For the cover artwork polyester fabric was used, and the artwork was designed through graphic design software.

The performance system designed through Max utilised the *fzero~* object for pitch detection (see 4.4.2). The *split* object was used for pointing to a range of frequencies in relation to the pitch to be tracked. For spatialisation, the *spat.pan~* object was chosen, with output set to 6 channels. Through the *spat.viewer* object, the actual speaker position layout could be simulated, allowing sounds to navigate precisely from one speaker to the other (see 4.1.4).

5.2.4 Compositional Structure and Material

The composition is notated as "senza tempo" and with no rhythmic notation. The only time guidance is determined by the number of seconds a passage should be executed. This was chosen in order that the performer could perform freely and focus on their control over interaction with the pitch and amplitude tracking mechanisms. It was divided into 3 sections, A (Linear Patterns), B (Shapes) and C (Synthesis). The speaker numbers for spatialisation were noted in the score. The first section (Figure 21) presents a *linear* relationship between the sound navigation around the stage and the pitch played. Thus, the same note ordering is always equivalent to the spatial position ordering.

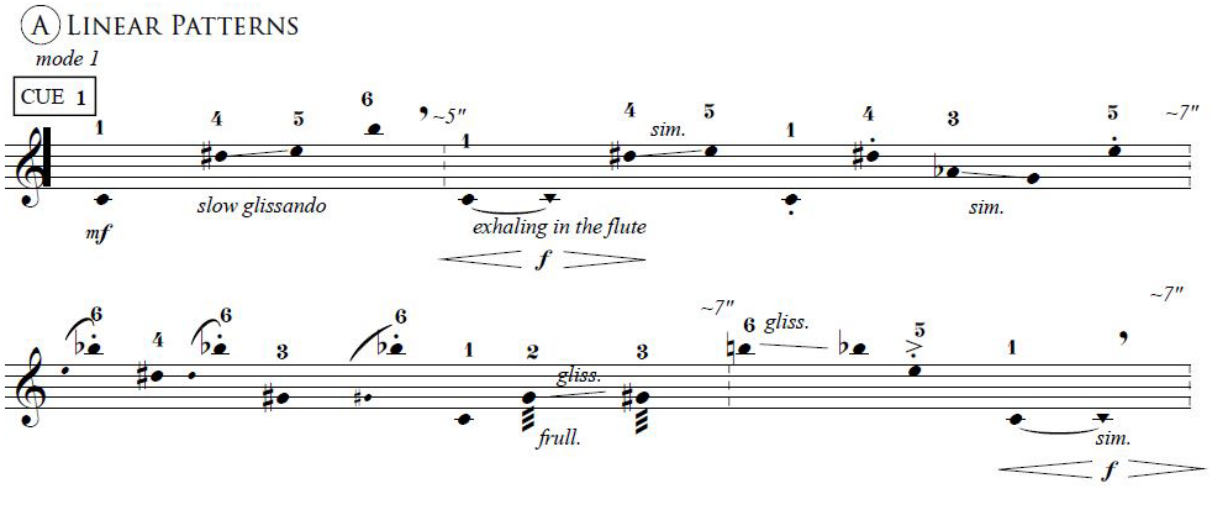

Figure 21. Bi-dimensional: Section A.

In *Section B* (fig 3.2), the relationship between notes and spatial positions is different. The idea of *shapes* was suggested, where melodic patterns correspond to specific speaker positions in a variety of ways, such as in "zigzag" motion (Figure 22). The last section combines the two previous approaches.

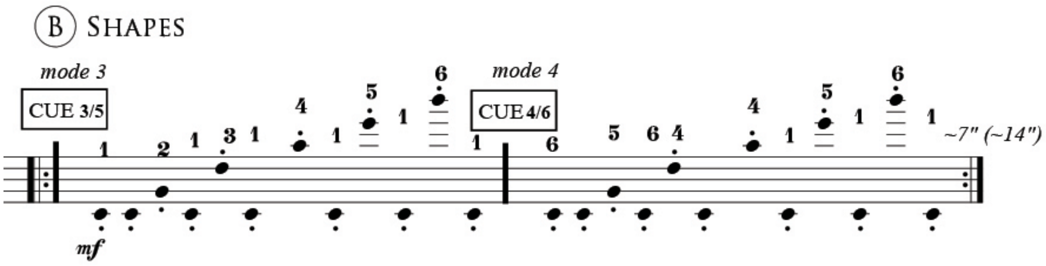

Figure 22. Bi-dimensional: Section B.
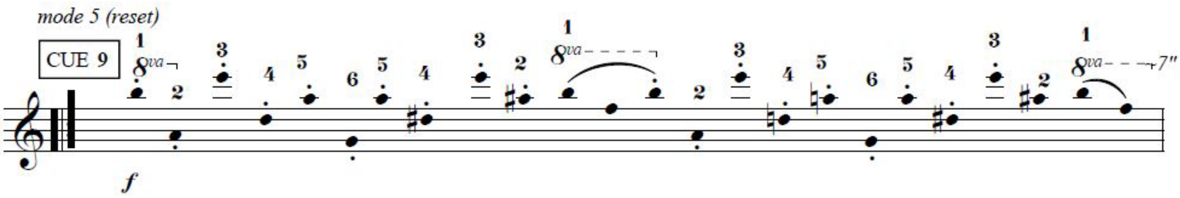
Figure 23. “Zigzag” idea, pitches alternate between low and high notes while speaker positions increase linearly.

Eighteen cues were provided throughout the score so that the performer could trigger (by using a footswitch) seven different modes, changing the electronic sounds and tracking systems. Pre-designed synthesised sounds were created for accompanying textures. They were all made to sound continuous, without any rhythmic changes. This was desired to create the effect of continuous sound motion throughout the multichannel system.

Different sets of notes were chosen during the compositional stage; they present large interval gaps, which allows a high range of discernment between notes for more accurate pitch detection. In Section A, the note set is composed of: G3, D4, D#4, A#4, B4 and F#5 (Figure 24). Other occurrent notes were not pitch tracked and only used as ornaments.

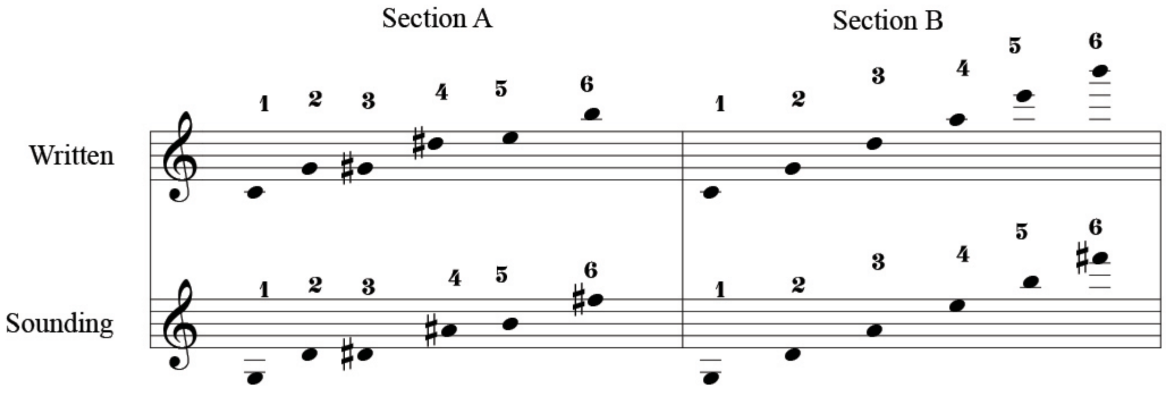

Figure 24. Bi-dimensional: Note sets for Section A and Section B.

In Section B, the note set is composed of: G3, D4, A4, E5, B5 and F#6 (Figure 24). In some subsections (cue 8 to cue 10), note tracking was realised by amplitude instead of pitch detection, thus notes were notated with staccato for better tracking efficiency.
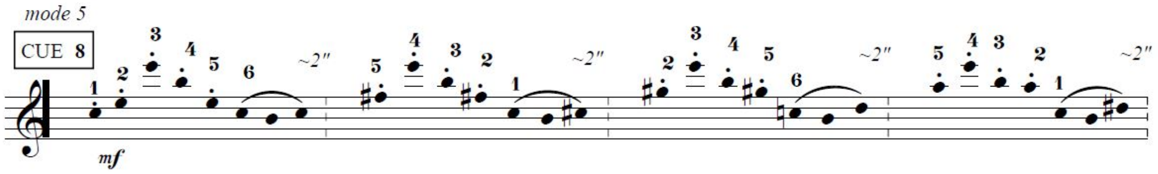
Figure 25. Bi-dimensional: Staccato notes in Section B.

The final subsection of Section B is comprised of multiphonics[5] (Figure 26). Each fundamental note of a multiphonic sound triggers a different synthesised sound, which carries a succession of notes in harmonic series and rotates in accelerando throughout all speakers. This effect is pronounced again at the final bar, at the piece’s conclusion.

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[5] Multiphonic is an extended technique for producing multiple pitches at once.

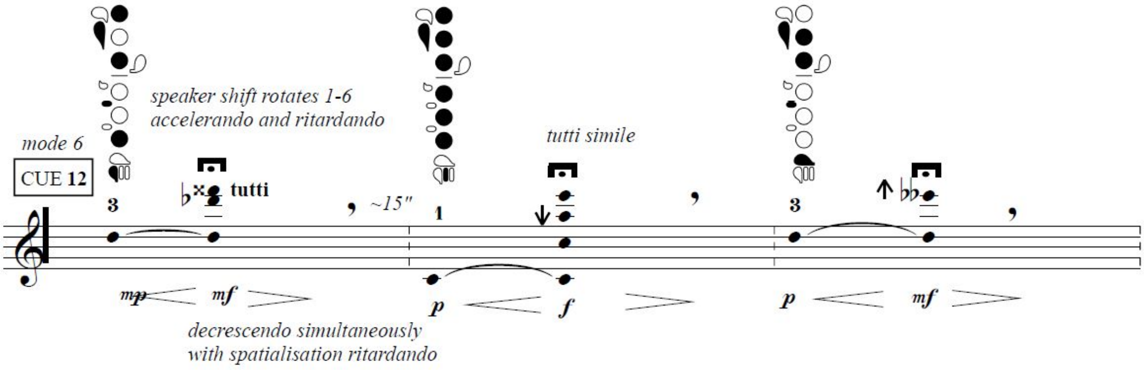

Figure 26. Bi-dimensional: Multiphonic sounds.

5.2.5 Outcomes

Bi-dimensional was performed by Richard Craig at the Victoria Gallery & Museum in Liverpool in March 2017, as part of the Open Circuit Festival (Figure 27). The total performance length was approximately 9 minutes.

Figure 27. Bi-dimensional: performance at the Open Circuit Festival.

A *sound canvas* (5.7) was produced by using the audio recording and the Max patch to reinterpret the interactive system of pitch and amplitude detection in a new media format. Since Max requires Windows or iOS, it could not run on a microcontroller or Raspberry PI machine, which was the approach taken before for producing the other sound canvas experiments. Thus, the solution was to devise a new system using a Lenovo Ideacentre Stick, operating Windows 8 and therefore running Max in a compact and power-saving interface (see 5.7.3.1).

Along with this solution, control operation (such as to switch off the computer or change volume levels) was provided by an Arduino board using the ATmega32u4, as this specific chip allows keyboard simulation. The Arduino was also used for connecting the lighting system to small LED lights (Figure 28). The sound was outputted through a compact six-channel USB sound interface.

Figure 28. Bi-dimensional: 100x35cm, 6-channel, sound canvas media. LED lights are activated along with loudspeakers hidden behind the fabric material.

In addition, the Max patch was edited so that sections of the composition would play only after the system detected “claps”, or any other sound that triggered the amplitude threshold. This allowed the work to be silent when not operating in front of an audience and offered a new feature for user interaction. The resulting artwork was exhibited at the Threshold Festival 2017 in Liverpool.

Figure 29. Bi-dimensional: Sound canvas on exhibition at the Threshold Festival 2017.

PART II – Sound-Light Compositions

5.3 Immanence

5.3.1 Concept

Immanence is a composition written for percussion trio and augmented instruments. It investigates the use of reactive lights on instruments and Wi-Fi connectivity for providing wireless control to performers. This can be achieved by attaching electronic devices to string bows and percussion mallets.

The title refers to the theory of immanence, in which the divine (i.e., supernatural religious entities and associated elements) is manifested in the material world, countering the theory of transcendence. This view relates to the work of the seventeenth-century philosopher Baruch Spizona (Spinoza, 1954), and it has been strongly associated with pantheism (Leon, 1933; Oakes, 2006). Thus, the composition title and its subtitles, found in different sections of the composition, were used to suggest a link between musical instruments and thoughts on spirituality and the concept of the divine. Throughout history, percussive instruments especially those that have an inharmonic timbre, such as bells and gongs, have shown a symbolic attachment to religious contexts. The composition is organised in five sections: *Deus sive Nature*; *Aural Energy*; *Hypokeimenon*; *Zoetic*; *Divinus*.

This composition was dedicated to the Brazilian percussionist Maestro Reinaldo Calegari.

5.3.2 Objectives

1. To explore reactive lights by attaching devices to percussion mallets.
2. To explore the use of an accelerometer sensor transmitting data via Wi-Fi for interactive digital sound processing.
3. To explore techniques for percussion to create continuous sounds (*stasis*) and spatialisation—exchanging sound levels between instruments.

5.3.3 Design

Two devices were produced to be used in this project’s live performance. *Device #1* was made to be attached to bows and to send accelerometer data wirelessly, whereas *Device #2* was made to be attached to mallets and the tubular bells, in order to produce light effects that react to vibration.

IMU (inertial measurement unit) devices can track the XYZ coordinate motion of an object in space. Technology advancements in the last decades have facilitated the inclusion of IMU devices for the performance arts (Fléty, 2005; Aylward and Paradiso, 2007; Hsu and Kemper, 2015). In addition, wireless communication protocols such as Wi-Fi and Bluetooth have allowed musicians to work with these accessories freely in space, without worrying about mistakenly unplugging cables and movement limitations. Commercially available devices as such do exist—e.g., *NGIMU* (X-IO, n.d.)—as well as electronic bows made specifically for this function—e.g., *K-Bow* (Rose, 2010; McMillen, n.d.). However, for this project a compact and low-cost option was preferred. The recent ESP32 line of microcontroller modules (first released in 2016), which integrates a Wi-Fi module, seemed to be a reasonable option for this project, allowing further experiments with electronic design.

Device #1 contained an ESP-WROOM-32 microcontroller unit, an accelerometer, RGB LED lights and a lithium battery with USB charging circuitry. Three of these small devices were produced, enclosed in 3D-printed cases, and attached to string bows. The ESP-WROOM-32 was selected as it integrates a 32-bit microcontroller with Wi-Fi capabilities, allowing the accelerometer data to be sent directly to a computer (Espressif Systems, 2019). This device was attached to bows so it could produce data from the performer’s hand motion (X, Y, Z axes) and send via Wi-Fi UDP to a computer in the performance room. The data was immediately transmitted to a Cycling '74’s Max patch, which receives the UDP data through the *sadam.udpReceiver* object, available from the Sadam library (Cycling '74, n.d.c). RGB lights were added to indicate the Wi-Fi connection status.

Finally, the accelerometer data was used to digitally process sounds that were recorded from on-stage microphones. The digital processing consisted of mapping the accelerometer data to the Max’s *freqshift~* object, which shifted the frequency of the original sounds. The processed sound was outputted from the sound interface's DAC to stereo loudspeakers.

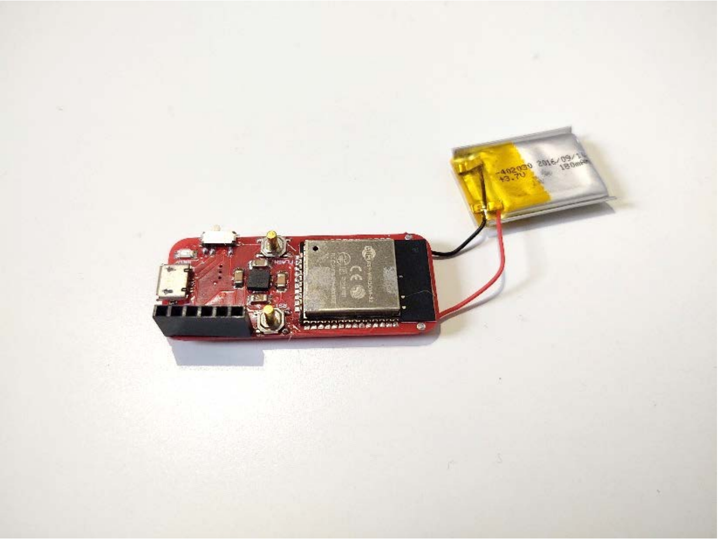

Figure 30. Immanence: Device #1, custom circuit board with ESP32, accelerometer and other components.

Figure 31. Immanence: Device #1 inside 3D printed case and attached to a string bow.

Device #2 integrates an Attiny84 microcontroller (Atmel, 2010), a vibration sensor (piezo disc), LED lights and a 3V battery socket. To make the operation of the mallet as light and natural as possible, it was important to make the device as compact as possible. Therefore, due to its low power functionality and size, the Attiny84 was selected, and with power provided by one CR2032 battery (20mm diameter and 3.2mm height). The vibration sensor was made by connecting a piezo disc and a 1M Ohm resistor to the microcontroller's ADC. The transducing properties of a piezo disc occurs in the form of piezoelectricity, in other words, generating electricity from mechanical stress.

Thus, the operation of *Device #2* consists of capturing mechanical stress from mallets striking instruments (e.g., cymbals), which vibrate the piezo disc and send analogue data to the microcontroller. The microcontroller was programmed to illuminate LEDs for each new mechanical input that triggered values above a pre-configured threshold. In this respect, a trimmer potentiometer was added to allow the performer to calibrate the threshold of the device prior to the performance, and an additional trimmer potentiometer was also installed to allow various light mode options (e.g., setting the duration that the lights should stay active once triggered).

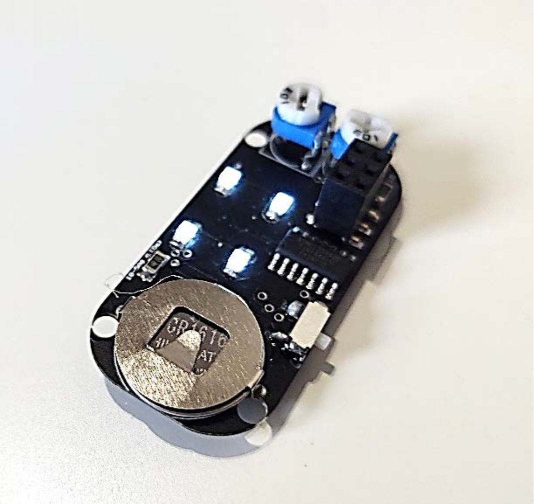

Figure 32. Immanence: Device #2, custom circuit board with Attiny84, LED lights, piezo disc (at the back) and other components.

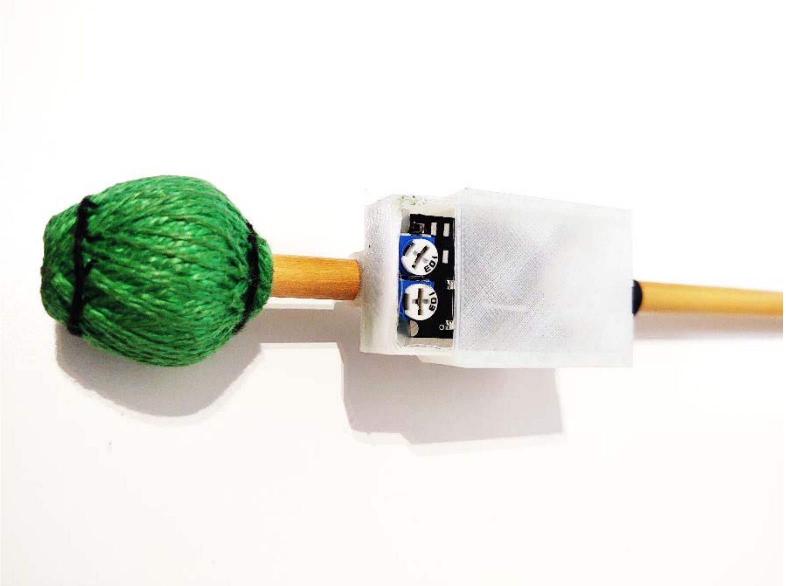

Figure 33. Immanence: Device #2 enclosed with 3D printed case and attached to a mallet.

5.3.4 Compositional Structure and Material

The instrumentation consists of different sets of suspended cymbals, one tam-tam, one zil bell and one set of tubular bells. In the percussion family, these are instruments that have metallic materials and demonstrate strongly inharmonic timbre, relating to instruments used in religious contexts (e.g., bells in churches or gongs in monasteries) and thereby having an association with the proposed context. The different sets of cymbals were selected to provide a larger variety of sounds, and the cymbal pairs for allowing spatial effects to be explored.

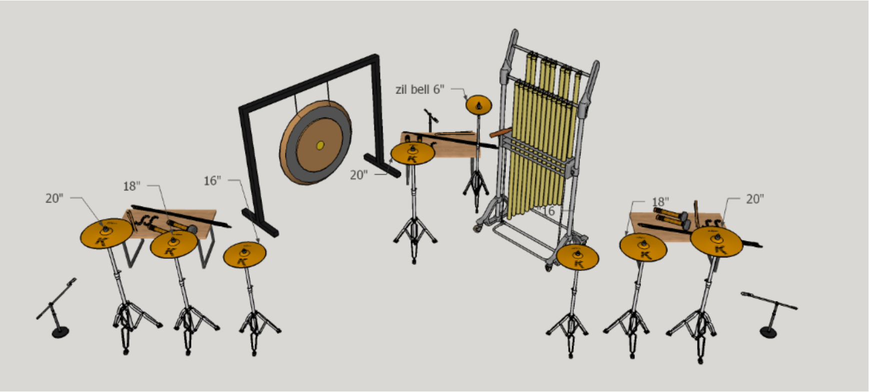

Figure 34. Immanence: Instrumentation and stage layout.

This composition was divided into five sections: I, *Deus sive Nature*; II, *Aural Energy*; III, *Hypokeimenon*; IV, *Zoetic*; V, *Divinus*. Each section corresponds to a different playing technique (Figure 35).

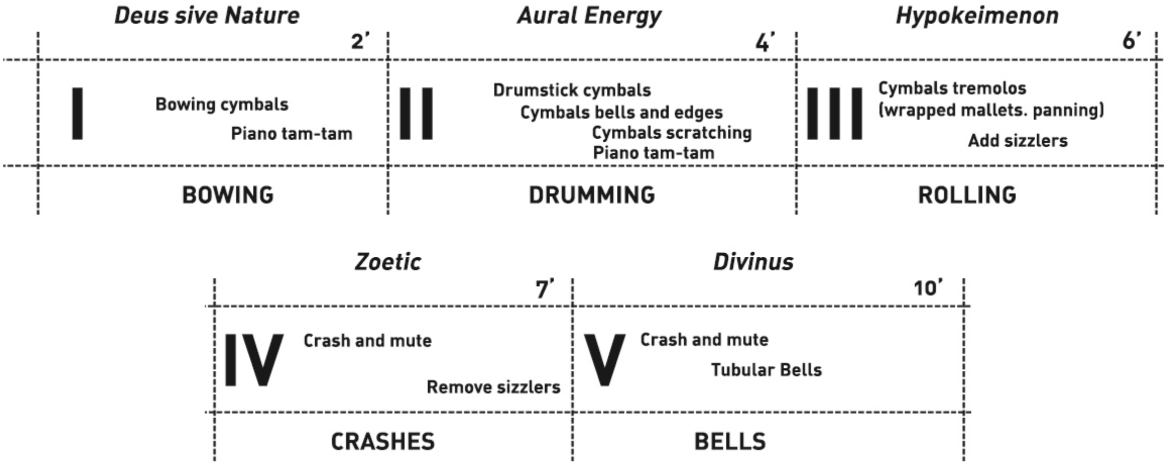

Figure 35. Immanence: Structure.

The first section, *Deus sive Nature* (God or Nature), explores the sound of bowed cymbals in parallel with processed sounds. As the microphone captures the cymbal sounds, data indicating the bow position is sent through the electronics attached to the bow (*Device #1*). The three performers alternate bowing on different cymbals, generating sounds at separate times and occasionally having the same onset. The tam-tam joins in bar 14, and at this point, the trio begins to perform the same rhythms in parallel.

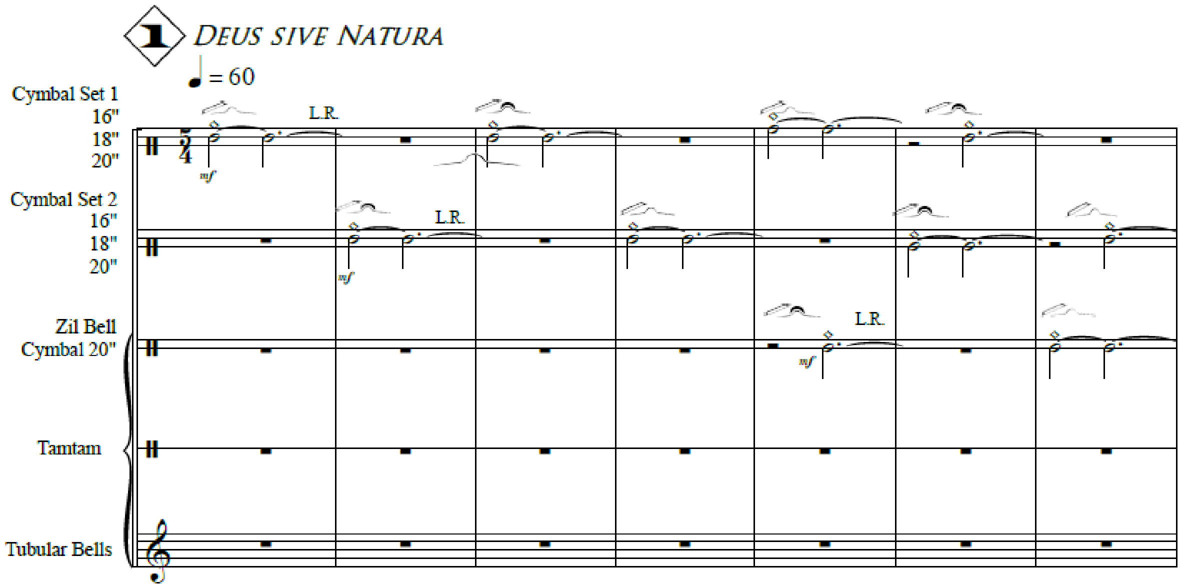

Figure 36. Immanence: Section 1, bowing cymbals.

The second section, *Aural Energy*, explores the sounds of drumsticks on cymbals. It contains rhythmic motifs that end with the sounds of the cymbal bells (domes). The section continues with dynamic explorations by playing on the cymbal edges and cymbal scratching sounds.
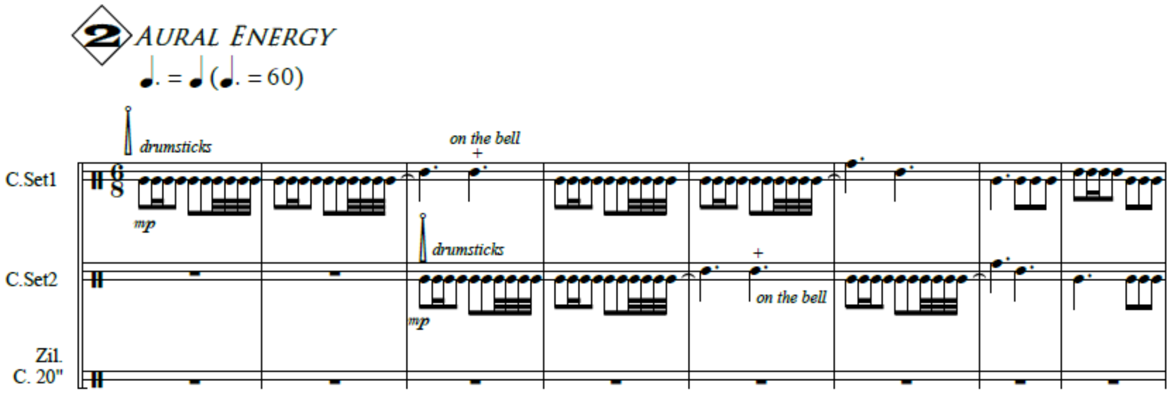
Figure 37. Immanence: Section 2, drumsticks on cymbals.

Hypokeimenon (the underlying thing), the third section, symbolises the metaphysical concept of searching for the essence of a material that is going through change. This section is performed with wrapped mallets to allow dynamic control with tremolos. Tremolos are used in the entire section and alternate between the two performers at the corners of the ensemble layout. This motion exchange suggests a spatial effect where sounds appear to be “panning”. To accomplish this, it was important to have the same timbre at distant stage points, thus the same cymbal size and model was utilised by different performers. In bar 120, chain sizzlers were attached to vary the timbre, introducing a new colour to the same dynamic scheme.

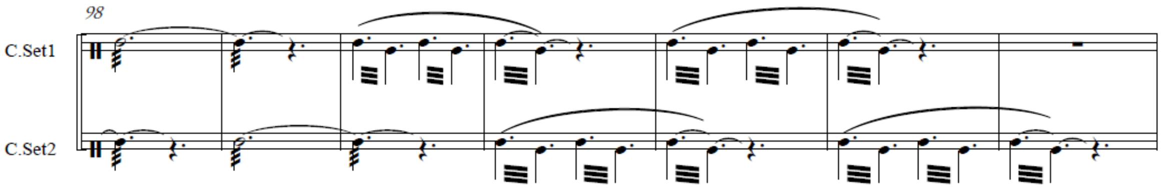

Figure 38. Immanence: Tremolo exchanges.

The fourth section is *Zoetic* (vital). Here cymbal muting was employed for creating a new type of texture, which is again exchanged between performers.

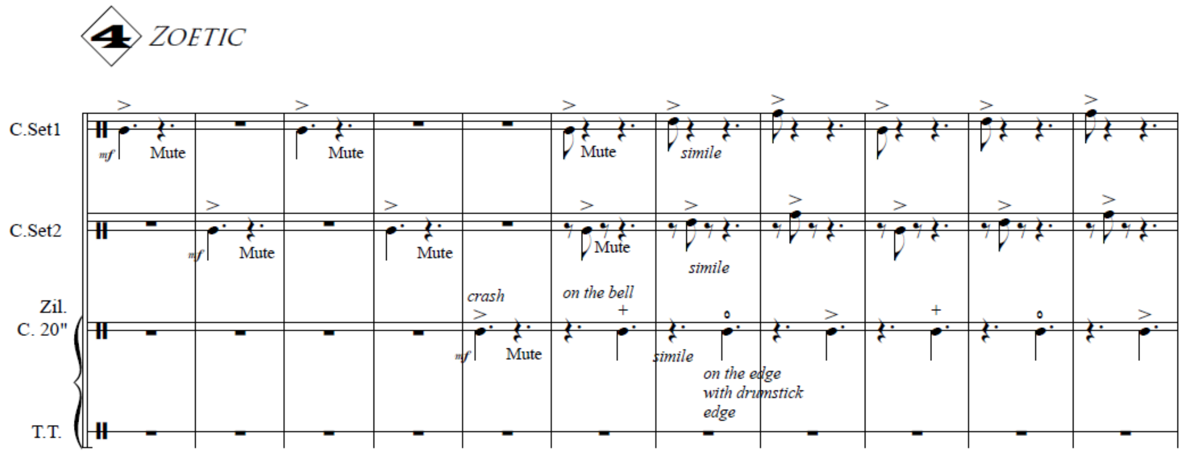

Figure 39. Immanence: Section 4, cymbal muting.

The final section, *Divinus* (divine), introduces the tubular bells in a sequence of major seconds, as in a whole tone scale (C, D, E, F#). In this section all previous techniques reappear; thus, a mixture of bows, drumsticks and wrapped mallets is employed.
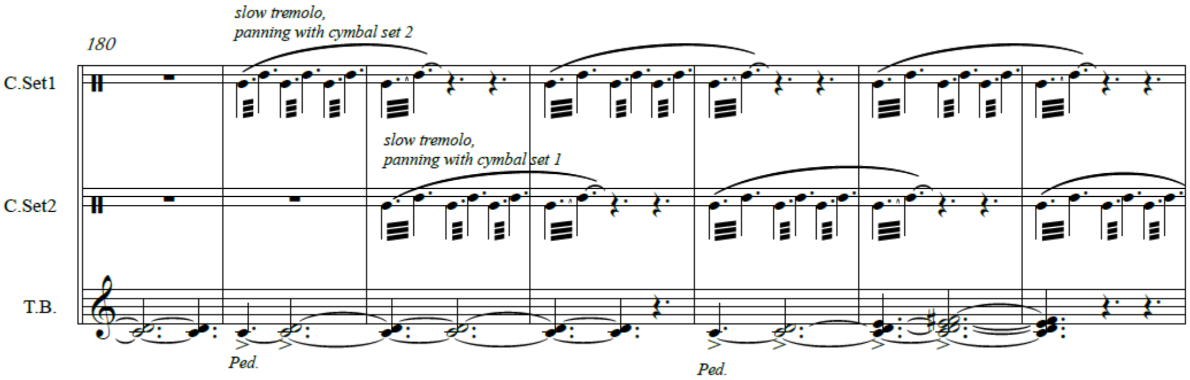
Figure 40. Immanence: Section 5, tremolo exchanges and tubular bells.

5.3.5 Outcomes

Immanence was performed on the 1st of November of 2019 by Line Upon Line, at the Open Circuit Festival. The total performance length was approximately 11 minutes.

Some performance issues were identified during rehearsals. For instance, initially, the piece had been written with indications for bowing the tubular bells. However, in the rehearsals the sounds and the mechanics of bowing the bells were unsatisfactory—the technique for bowing the bells was troublesome and the sound produced was too weak and quiet. In order to replace this effect a crotales and a triangle were therefore used, proving better results.

The electronic devices designed for this project were successfully implemented. Wi-Fi communication through the ESP32 microcontroller worked without any issues, proving to be an efficient alternative to wires, which in the case of string bows would be uncomfortable for performance. The LED lights on mallets demonstrated another way for the application of light in concerts, combining the visual and the auditory effectively. These two methods could be further explored with other instruments (e.g., using Wi-Fi bow with string instruments).

Figure 41. Immanence: Performance by Line Upon Line, mallets with LEDs.

Figure 42. Immanence: Performance by Line Upon Line, string bow with accelerometer and Wi-Fi.

5.4 Organoids

5.4.1 Concept

Organoids was inspired by the work of Dr Raphaël Levy[6] and microscopy techniques that employ laser beams for scanning biological cells. Lasers have multiple applications in several fields and in music they can be used for amplifying acoustic vibrations, converting sound stimulus to the visual domain. For this, a mirror can be mounted on a tuning fork, which vibrates and reflects the laser beam. The resulting effect is known as *Lissajous Figure*.

For this composition, a device comprised of three lasers and mirrors placed on small loudspeakers was developed. The device responds to microphone input, assigned to the composition’s trio instrumentation: bass flute, baritone saxophone and violoncello. This instrumentation was chosen due to their similar range aspect, allowing instruments to harmonise at lower frequencies corresponding to the device’s tuning resonance.

Organoids are simplified versions of organs produced in vitro (outside an organism). This title suggests a metaphor for each instrument's organic nature that is visually shown through the laser system, representing organoids in the process of microscopy imaging.

5.4.2 Objectives

1. To explore the use of laser light in performance.
2. To design a laser beam device for interactive music performance.
3. To compose music by selecting sound combinations between three instruments that can produce an interplay of Lissajous figures.

5.4.3 Design

This project aimed to use a dynamic laser device (also known as “laser scanner”) to project *Lissajous figures* in response to the frequencies and dynamics produced by a bass flute, a baritone saxophone and a violoncello. Lissajous figures are light shapes created by vibration, discovered by Jules Lissajous in the mid-nineteenth century (Ashton, 2005). Combined music intervals, such as a fifth, produce specific geometric shapes.

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[6] When this project began, Dr Raphaël Levy was a senior lecturer in biochemistry at the University of Liverpool and was a collaborator in the 8^3 project organised by PRiSM, which aimed to bring composers and scientists together. Dr Levy has published several papers in the fields of biological imaging and gold nanoparticles and is currently working at the University Paris Sorbonne-Nord.

Generating Lissajous figures via laser could be realised with a laser light interface that allows ILDA[7] communication, as it enables laser devices to be controlled via analogue inputs. These devices are widely available in the stage lighting industry, however, due to their high costs and for design research purposes, a device called *Laser Mixer* was produced to accomplish the project's aims.

The *Laser Mixer* device utilises small mirrors attached to three loudspeaker drivers, which are connected to the laser pointers through 3D printed support and tripod mounting parts. The loudspeakers have a 3W power rating and are 5cm in diameter. The laser pointers differ in colours: red (650nm, 5mW), green (535nm, 30mW) and purple (450nm, 20mW).

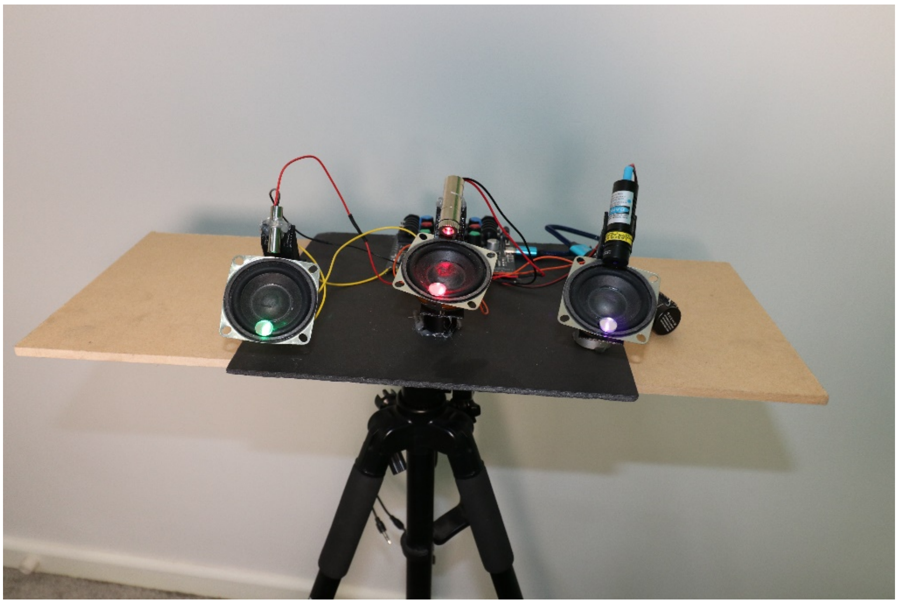

Figure 43. Organoids: The "Laser Mixer" device designed for performance.

To allow the mirror to take vibrations from the speakers, different methods for attaching the mirror were explored, such as attaching a spring to the speaker, covering the speaker with a balloon, or gluing the mirror directly on the speaker's surround (the rubber piece). The spring failed to reproduce visual shapes accurately as it added properties of its shape. The balloon produced good results but proved to be difficult to "tune"; with time its stress changed and thus the frequency response to the visual output also changed. Gluing the mirror to the speaker's surround proved to be the most robust design and thus became the preferred method.

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[7] The International Laser Display Association (ILDA) has defined standards for laser projectors including the 'ILDA Standard Projector'. Projectors based on this protocol include a DB-25 connector to transmit signals, allowing control of X and Y positions, RGB colour, among other parameters (ILDA, 1999).

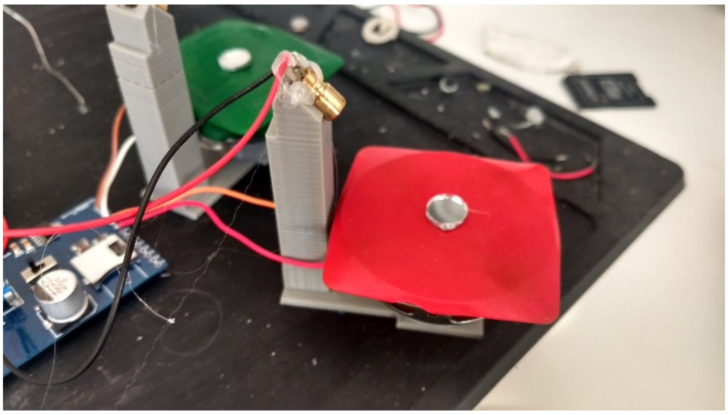


Figure 44. Experiments with balloons on loudspeaker drivers.

Figure 45. Experiments with mirrors attached to a variety of small loudspeaker drivers.

In addition to the loudspeaker preparations, a circuit board for mixing three inputs to the three outputs, with amplification (PAM8403 amplifiers) and USB connection for 5V power supply was produced. Through these input-output mixing possibilities, different signals could be joined or separated, enabling instruments to create Lissajous figures when harmonising in the same signal (captured via microphones). Furthermore, this allowed instruments to be routed to any of the laser light outputs, offering colour choices.

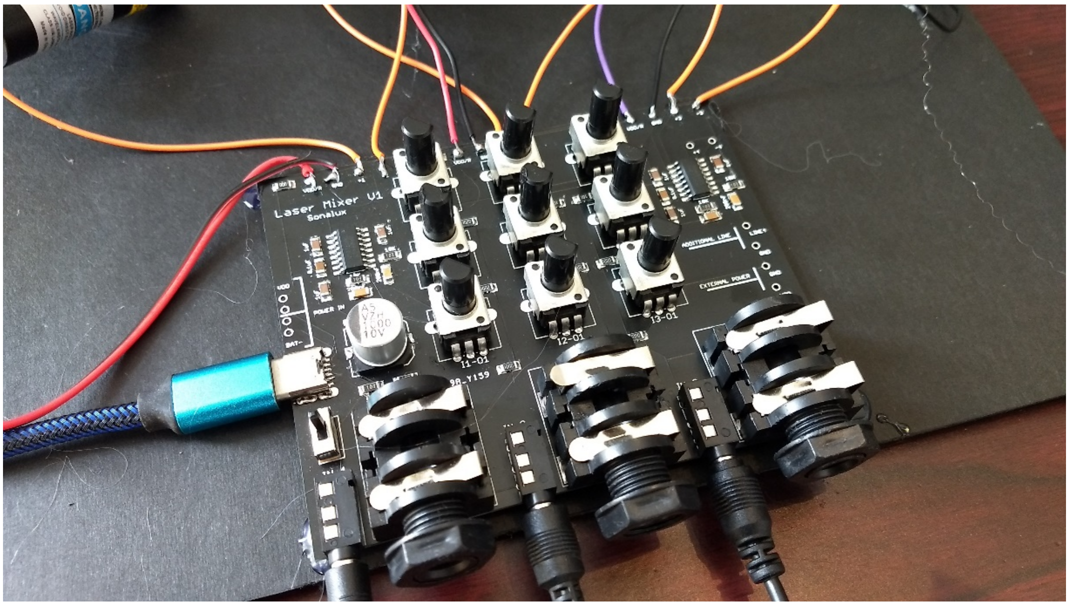


Figure 46. The Laser Mixer's circuit board, with amplifiers, USB-C connector for power supply, line inputs (3.5mm or jack) and 6 potentiometers for routing the signals.

5.4.4 Compositional Structure and Material

The instrumentation was selected due to the low-frequency ranges, with the lowest notes being C2 (cello and baritone saxophone) and C3 (bass flute). This allowed the instruments to harmonise and thus generate specific *Lissajous figures*.

Since the laser device responded well (a perfect circle) when receiving a 185Hz (F#3) sine signal, an F#3 note was taken as the point of departure for all harmonic ideas.

The structure comprises of *Introduction*, *A*, *B*, *C*, *D*, *E* and *F*. The introductory section begins with the cello playing a sustained F#3, occasionally adding notes to harmonise and generate shapes (Figure 47). The notation indicates that the bass flute and the baritone saxophone should be mixed into the same audio signal, in order to provide a fused texture and the same visual output. Thus, they intermittently sustain the F#3 note, pronouncing the central note and supporting the cello's harmonic concept.

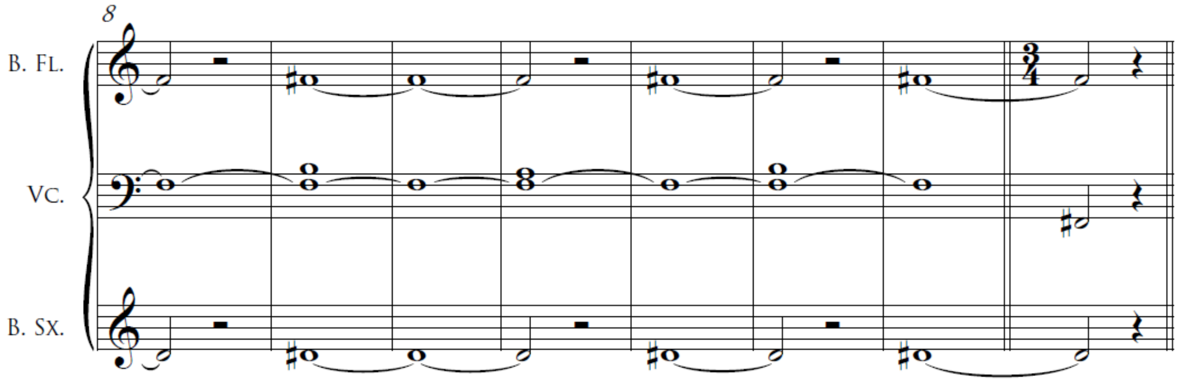


Figure 47. Organoids: Introduction, bars 8-15.

In *Section A*, the flute and saxophone pair begin to harmonise. In bar 30, all instruments operate as individual signals for the laser device. A melodic line based on the Melodic Minor scale appears to create a different type of visual output, moving from the saxophone to the cello.

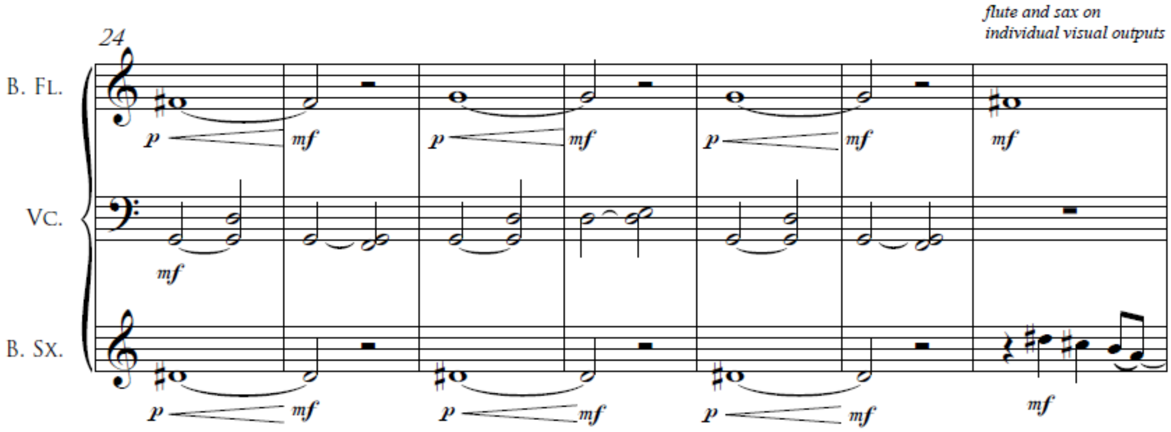


Figure 48. Organoids: Section A, bars 24-30.

In *Section B*, the saxophone plays multiphonics, which were chosen due to the Lissajous figures that they produced. Prior to notation, a large variety of multiphonics were tested with the laser device and the most effective were selected. In this section, the flute and the cello support the saxophone with a texture surrounding the central note.

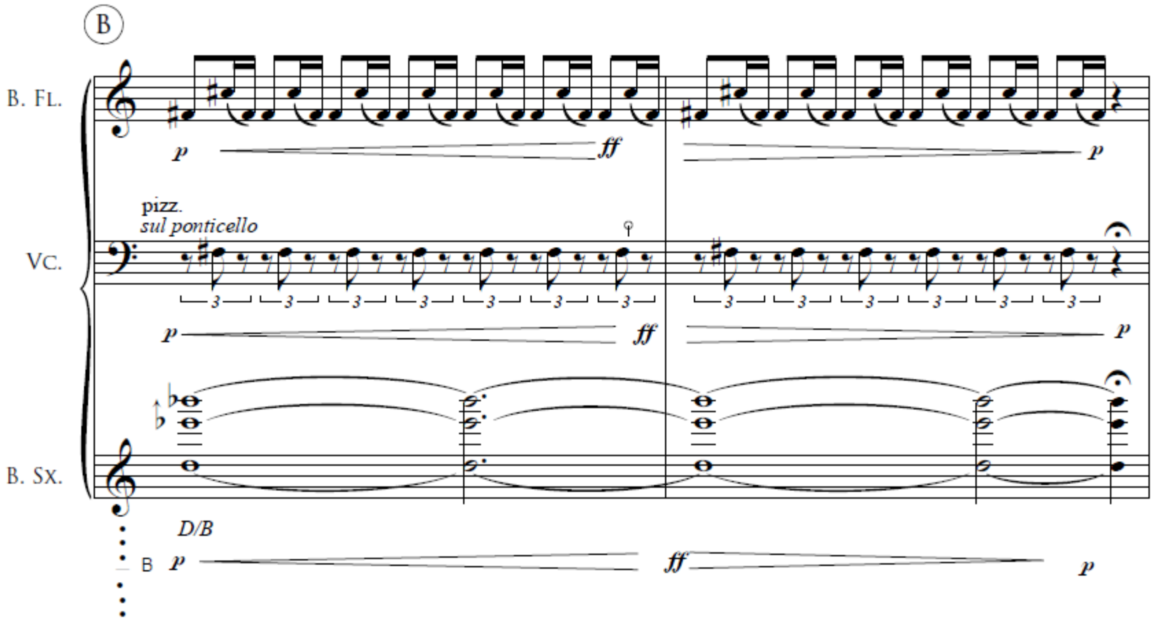


Figure 49. Organoids: Section B, saxophone multiphonic sounds and supporting texture by the other instruments.

In *Section C,* glissandi on the cello and other articulations are explored, generating new visual effects. In bar 45, a harmonic progression of two chords appears. These chords can be heard as a D moving to Dm7, with omitted fifths.

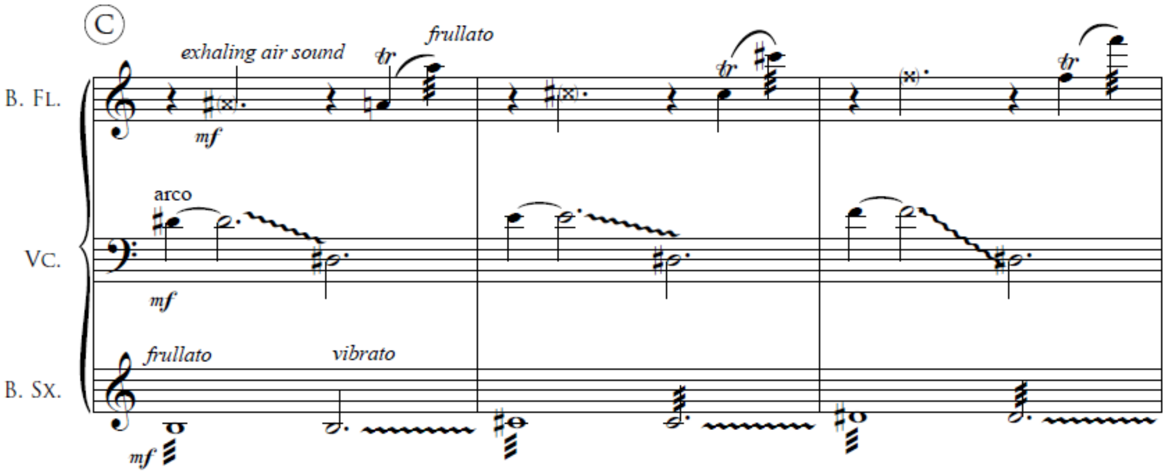



Figure 50. Organoids: Section C, other articulations appear for new visual effects.

In *Section E,* fast melodic lines based on the Melodic Minor scale are employed to generate new types of visual output. In bar 61, the flute and saxophone are paired again in order to generate visual shapes through harmonisation. This same bar repeats with expanded durations in bar 62 and 63.

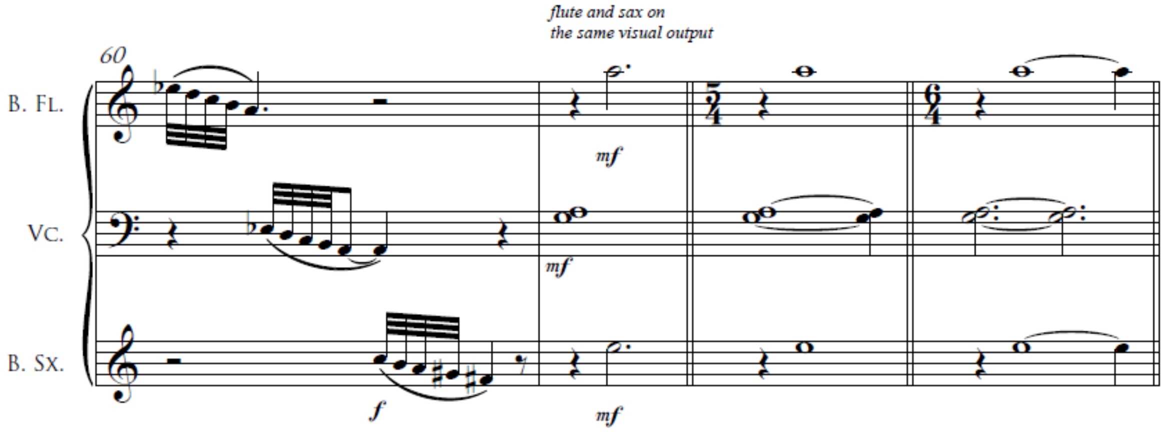



Figure 51. Organoids: Section E, bars 60-63.

In *Section F*, a new harmonic progression appears. Crescendo dynamics are employed to create an effect in which each new visual shape slowly increases. From bar 72, a variation of bar 24 to 31 appears, remembering a distinct melodic line from section A, and concluding the piece with the first harmonic progression of two chords, D and Dm7, however, this time they appear in inverted order, as Dm7 moving to D.

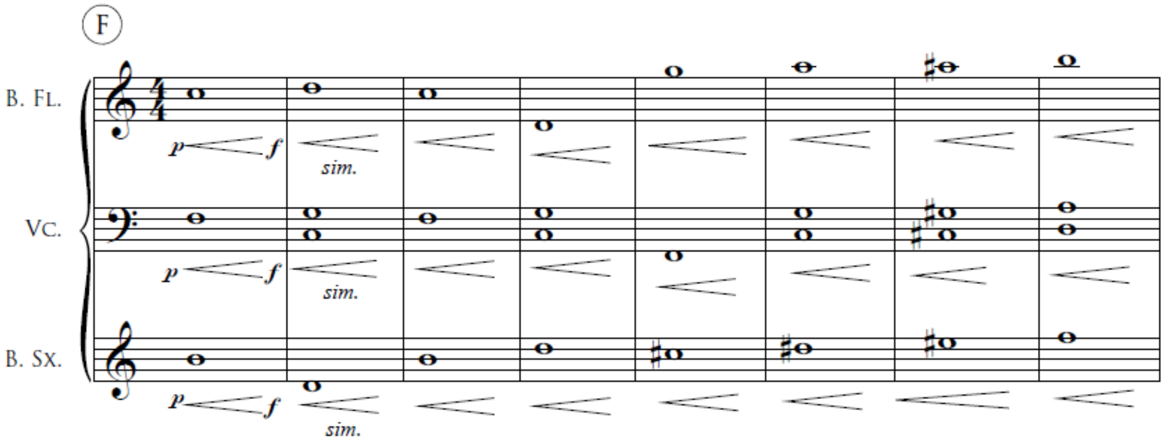


Figure 52. Organoids: Section F, bars 66-73, harmonic progression.

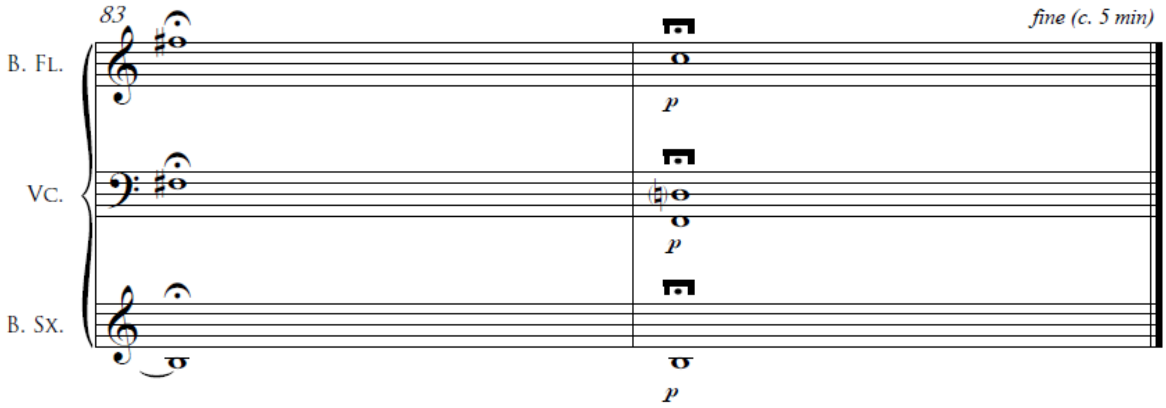


Figure 53. Organoids: Final chords.

5.4.5 Outcomes

Organoids was recorded by musicians of the Liverpool Philharmonic Orchestra in March 2021 and video-recorded by the Riot Ensemble in June. The Riot Ensemble performance was presented online in July 2021 through the PRiSM 8³ project, a concert event organised by the PRiSM research centre based at the RNCM in Manchester. The laser projection was recorded separately and combined with the ensemble footages in post-production. Unfortunately, due to low light conditions and the fast speed of lasers, video recording the laser visuals proved difficult and did not produce the best results. The resulting shapes can be much more visible during a live performance. Furthermore, because the recordings were delayed for months due to the COVID-19 pandemic, the laser device did not function properly, resulting in unexpected visual patterns.

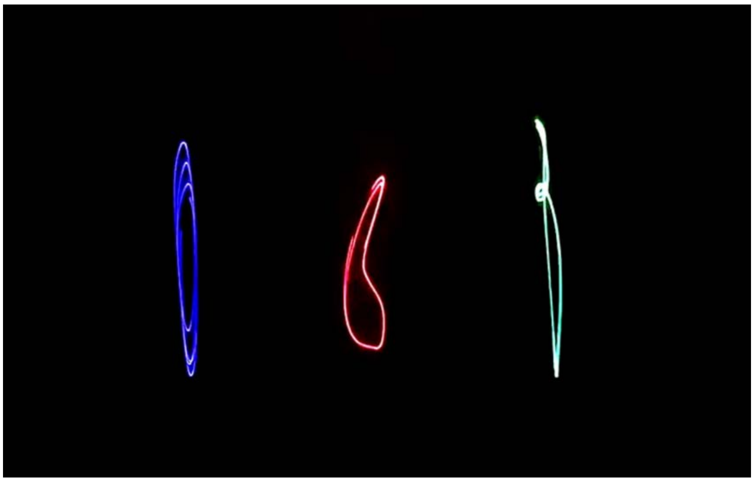


Figure 54. Organoids: Laser projection. Bass flute: left signal; Cello: middle signal; Baritone sax: right signal.

5.5 Future Lights

5.5.1 Concept

Future Lights is a composition for violoncello and lights in which various lighting effects interact with the performer to create a multisensory experience. Light beams and luminosity change in response to the cello's frequencies, dynamics, and rhythms.

The inspiration for this work comes from two events. Firstly, the composition is inspired by the culmination of digital lighting technology, which today allows composers to further expand their ideas to stage lighting control. Secondly, the 2020 pandemic’s impact in the performance industry has been motivating streamed concerts, however, these concerts often lack several aspects of the real-world experience. Therefore, an interactive system was designed for *Future Light*’s première, which went live on the 1st of September 2020 via YouTube. This system allowed live audience interaction through chat messages. The audience was able to change light colours, camera positions and produce “clapping” sounds at the end of the performance, which allowed the audience and performer to feel more engaged with the live aspects of a virtual concert.

5.5.2 Objectives

This project began from research on virtual stage interfaces for performances during the UK’s lockdown, from March to July 2020. This evolved to a study and the development of an interface for virtual stage lighting. With a scheduled online performance for the 1st of September 2020, it was sensible to compose for solo performance due to the social distancing guidelines set in the UK.

The project aimed to explore several mapping possibilities from sound to light control, exploring the development of an interface through Cycling '74’s Max, in combination with Jitter and OpenGL shaders. In addition, due to the increase in online performances during the 2020 pandemic, exploring new ways of presenting live performances was another aesthetic objective. Thus, a secondary aim was to implement an original system for online audience interaction. The technology for requesting comments from live videos on YouTube, YouTube’s Data API (YouTube, 2021), is today steady and well-documented. Initial tests confirmed this approach could work, and all that was required was to integrate HTTP code into the Max patch and decide which parameters should be changed by the audience.

This study, therefore, aimed to:

1. Design virtual lights within different contexts and simulate stage lighting.
2. Control virtual lights in real-time with a musical instrument.
3. Explore different mapping parameters for sound to light interaction.
4. Develop a live interactive interface for online audience.

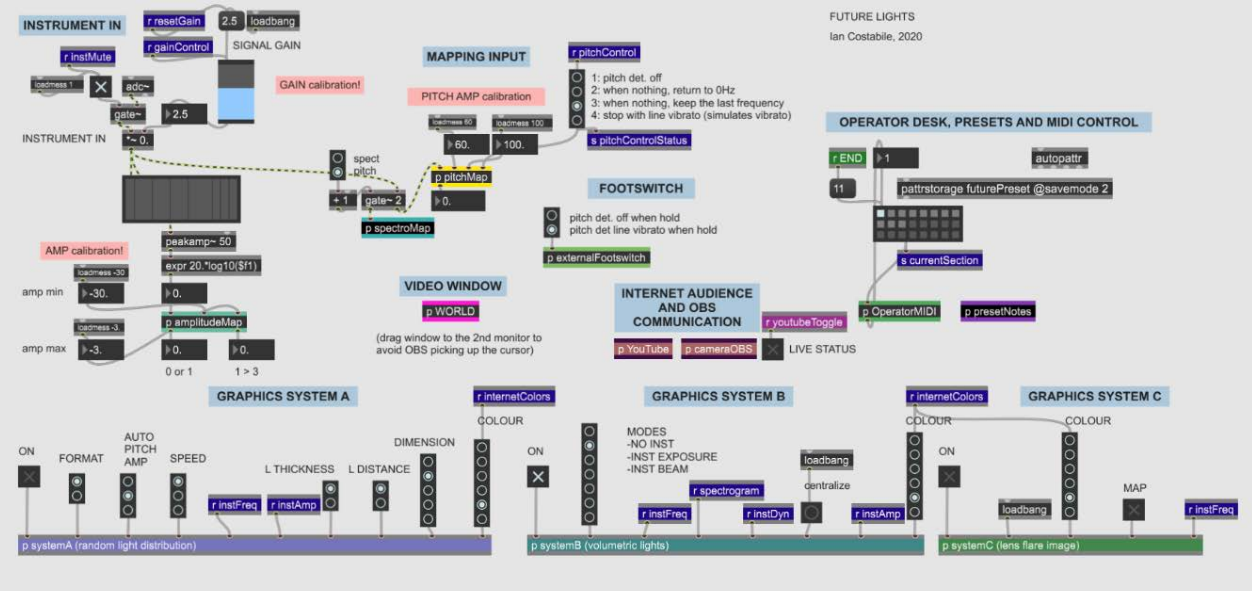
5.5.3 Design

This composition utilised Cycling '74's Max for creating a multifunctional interactive interface. A Max patch was created to process the violoncello's audio signal, generate real-time visuals (using OpenGL) and receive live data from YouTube. For performance, a green screen was set behind the performer and OBS Studio was used for chromakeying, capturing sound and image, and operating the live streaming.

To create the real-time interaction from the instrument's signal to the lighting control, three different methods were applied:

a) Frequency detection with Max's external *fiddle*~ object (Puckette, Apel and Zicarelli, 1998).
b) Spectrum analyser with Max's *fffb*~ object.
c) Amplitude peak detection with Max's *peakamp*~ object.

These methods are discussed in detail on Chapter 4 (4.4.2).



1: pitch det. off
2: when nothing, return to 0Hz
3: when nothing, keep the last frequency
4: stop with line vibrato (simulates vibrato)

pitch det. off when hold
pitch det line vibrato when hold

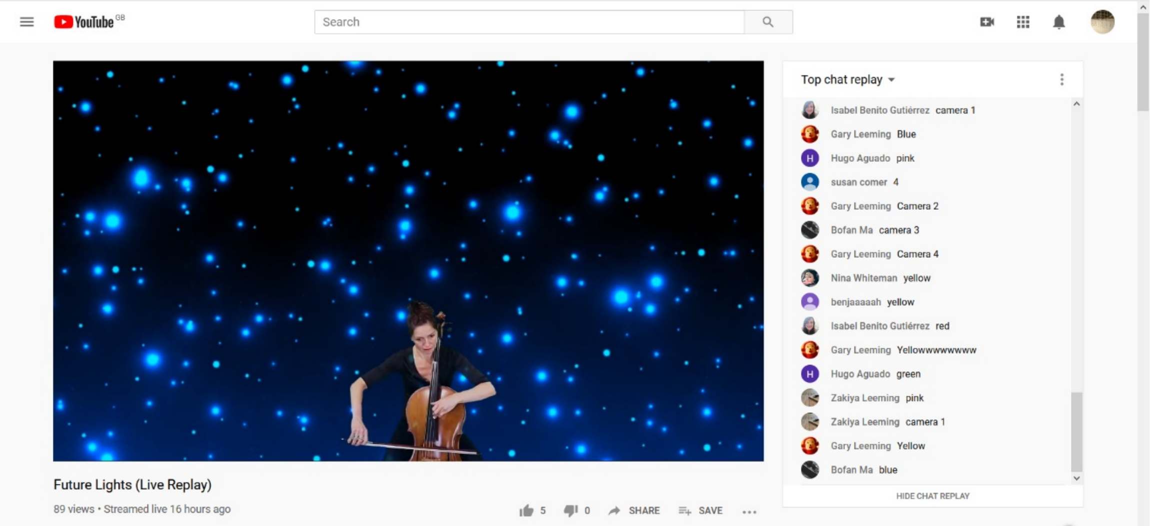
(drag window to the 2nd monitor to avoid OBS picking up the cursor)

Figure 55. Future Lights: Max patch screenshot.

For generating lights in Max different methods can be used. The Jitter library included in Max presents a variety of objects for working with graphics, thus virtual lights could be developed through these means. OpenGL is a library for rendering 2D or 3D graphics which can be accessed from Jitter objects. Because OpenGL can run its algorithms from the GPU (Graphics Processing Unit), it does not compromise the computer's CPU and it is much more efficient for managing graphics. In this case, an Nvidia GeForce GTX 1050 GPU running on a Windows 10 computer was used.

Further control and efficiency through OpenGL can be achieved by writing personalised programs called *shaders*. Shaders allow users to customise parameters for graphic objects, such as colour, position, texture and materials (Cycling '74, n.d.d). The language for writing these programs is called GLSL (OpenGL Shading Language) and Max allows users to write and compile GLSL codes through the use of three objects: *jit.gl.shader*, *jit.gl.slab* and *jit.gl.pix* (Cycling '74, n.d.d; Cycling '74, n.d.e; Cycling '74, n.d.f).

Three different shader codes were utilised in this project and classified as *Graphics System A*, *B* and *C*. The first was a modification of a shader code known as *The Universe Within*, a shader code available from ShaderToy, which is an online community for creating, learning, and sharing shaders (BigWings, 2018). This code is a visual representation of moving lights and lines, resembling constellations in the universe.

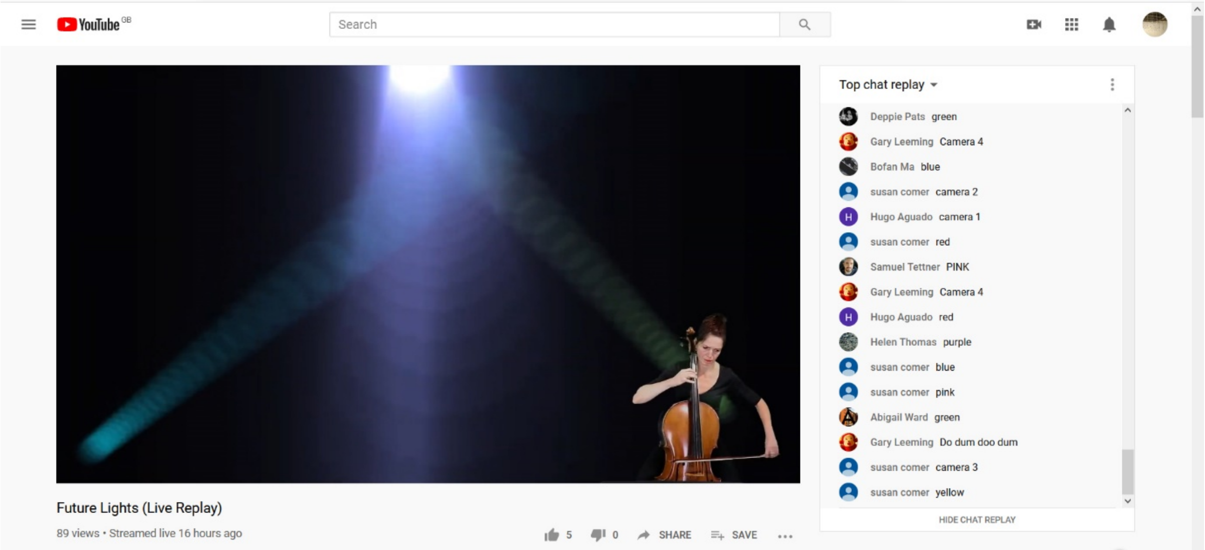


Isabel Benito Gutiérrez camera 1
Gary Leeming Blue
Hugo Aguado pink
susan comer 4
Gary Leeming Camera 2
Bofan Ma camera 3
Gary Leeming Camera 4
Nina Whiteman yellow
benjaaaaah yellow
Isabel Benito Gutiérrez red
Gary Leeming Yellowwwwwwww
Hugo Aguado green
Zakiya Leeming pink
Zakiya Leeming camera 1
Gary Leeming Yellow
Bofan Ma blue

Figure 56. Future Lights: Performance screenshot, Graphics System A.

Graphics System B was based on volumetric lights, taking as a starting point a Max patch available at Federico Foderaro's website (Foderaro, n.d.). This patch utilises an OpenGL shader to generate volumetric light scattering and it was based on an article by Kenny Mitchell

(Mitchell, n.d.). Volumetric lights are techniques in 3D computer graphics for simulating “point” and “spot” lights. Point lights are defined by a glow or halo around the light source, whereas spotlights have a cone of light or beam (Kerlow, 2004). By readapting this code and redesigning the Max patch structure, it was possible, therefore, to design an interface for simulating stage spotlights.

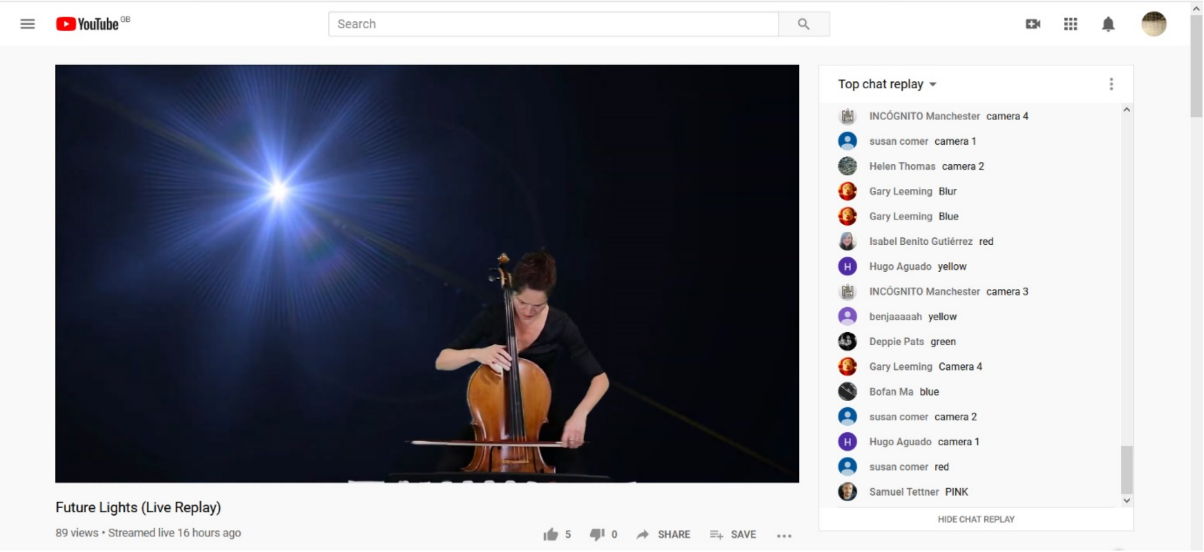


Deppie Pats green
Gary Leeming Camera 4
Bofan Ma blue
susan comer camera 2
Hugo Aguado camera 1
susan comer red
Samuel Tettner PINK
Gary Leeming Camera 4
Hugo Aguado red
Helen Thomas purple
susan comer blue
susan comer pink
Abigail Ward green
Gary Leeming Do dum doo dum
susan comer camera 3
susan comer yellow

Figure 57. Future Lights: Performance screenshot, Graphics System B.

Graphics System C was inspired by the “lens flare” effect. Lens flare is a common element in photography, caused by non-imaging light that enters the lens and reflects internally on the lens surfaces (Holben, 2013).

Through the *jit.movie* object in Max it is possible to display videos and images. Thus, an image of a photograph displaying the lens flare effect on a black background was loaded. By simply changing the brightness of the image, the flare object expands as it becomes brighter in its surroundings. This could be achieved by using the *jit.brcosa* object, however, since this parameter was expected to be controlled by audio signal interaction, a more efficient approach was devised through another OpenGL shader code.



Future Lights (Live Replay)

89 views • Streamed live 16 hours ago

INCÓGNITO Manchester camera 4
susan comer camera 1
Helen Thomas camera 2
Gary Leeming Blur
Gary Leeming Blue
Isabel Benito Gutiérrez red
Hugo Aguado yellow
INCÓGNITO Manchester camera 3
benjaaaaah yellow
Deppie Pats green
Gary Leeming Camera 4
Bofan Ma blue
susan comer camera 2
Hugo Aguado camera 1
susan comer red
Samuel Tettner PINK

Figure 58. Future Lights: Performance screenshot, Graphics System C.

The input-output mapping for Future Lights was configured as:

Section	Sound Input	System	Light Output
1	Pitch Detector	B	Brightness
2		B	Beam Angle
3		A	Motion
4		A	Motion
5		B	Brightness
6	Spectrum Analyser	B	Brightness
7	Amplitude Trigger	A	Motion
8	Pitch Detector	C	Brightness
9	Amplitude Trigger	B	Strobe
10	Amplitude Tracking	B	Brightness

Table 5. Future Lights: Input-output mapping.

In the Max interface, each section corresponds to a slot on the *preset* object, which can be controlled during the performance by an operator. For the live performance on the 1st of September 2020, MIDI controllers were linked to the Max patch for changing sections and for a variety of other functions, such as performance simulators (e.g., footswitch, audience interaction, gain adjustments, etc) in case of unpredictable flaws.

The footswitch utilised was created by using a A3144 hall sensor (magnetic) with an Arduino board (based on the Atmega32u4), capable of transmitting ‘ON/OFF’ status to Max via simulated keyboard commands or Serial communication. The latter was preferred as Max could only receive keyboard communication when its window was active, whereas with Serial it was flexible as it could receive data when other windows were active (such as OBS or YouTube). The structure of all technology used can be seen in Figure 59.

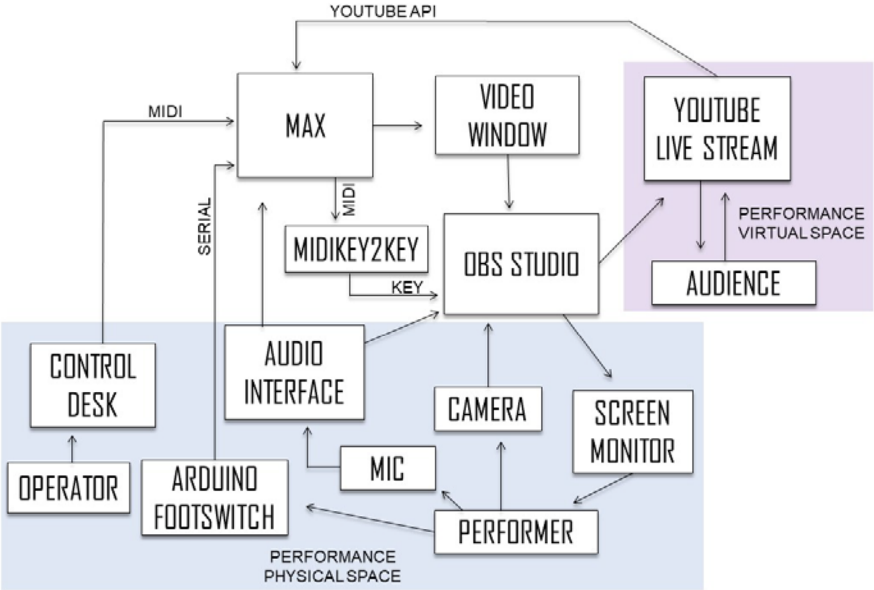


Figure 59. Future Lights: Technology structure diagram.

Audience Interaction System

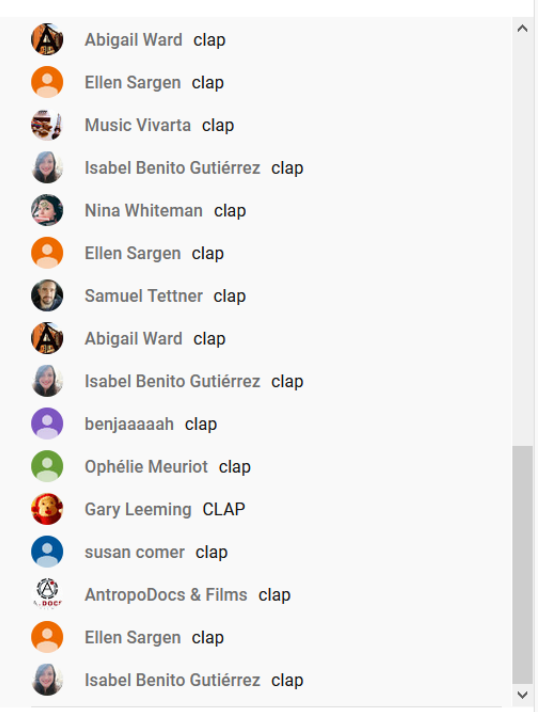
The field of Networked Music Performances (NMP) has a history of dedicated interfaces for audience interaction. For instance, the UpStage platform, created in 2004, has incorporated performances with audience webcams and moving cursors (Mills, 2019). However, the objective for Future Lights was to stream to a popular platform, without requiring any precise procedures for watching or participating. Considering streaming latency, or the time it takes for the stream to arrive at the audience, YouTube seemed a good platform for live performance, since it has an ultra-low latency live streaming setting.

Data requests from the YouTube Data API were accessed from the Max patch by using the *maxurl* object, which allows HTTP requests. The *dict* object, which is used for data storage, was also employed for gathering the incoming data. Other objects were subsequently added for filtering data and to extract only the latest chat message. The following commands were implemented for audience interaction:

```
green
yellow
blue
purple
pink
red
camera 1
```

```
camera 2
camera 3
camera 4
clap
```

By typing these commands into the chat window, the audience controls colours and camera positions (OBS scenes). The “clap” command, integrated only at the end of the performance, allowed the audience to generate clapping sounds. Five clapping recordings were selected. The number of clap commands sent is equivalent to the number of claps played simultaneously. In addition, to avoid excessive activity, colour changes were blocked in certain parts of the composition and camera changes were allowed only every 5 seconds.



Abigail Ward clap
Ellen Sargen clap
Music Vivarta clap
Isabel Benito Gutiérrez clap
Nina Whiteman clap
Ellen Sargen clap
Samuel Tettner clap
Abigail Ward clap
Isabel Benito Gutiérrez clap
benjaaaaah clap
Ophélie Meuriot clap
Gary Leeming CLAP
susan comer clap
AntropoDocs & Films clap
Ellen Sargen clap
Isabel Benito Gutiérrez clap

Figure 60. Future Lights: Screenshot of chat messages producing live interactive "clapping" at the end of the performance. Each clap message triggered a clapping sound.

5.5.4 Compositional Structure and Material

The piece was written alongside the light simulators and graphics systems. Melodic ideas of *glissandi* and small movements of semitones were projected for the control of light brightness and other effects. As it is a piece for solo instrument, the indication of *sempre rubato* and the absence of a time signature allow the performer to take more expressive control over the visuals. The terminology reserved for the sections were written in French as a gesture of sympathy to Georgina Aasgaard, who was the performer in the première. *Future Lights* was organised in 10 sections of different visual outputs:

1. La luminosité (the brightness)
2. Le faisceau lumineux (the light beam)
3. Mouvement d'etincelle (spark motion)
4. Jeu de profondeur (depth game)
5. La luminosité revient (brightness returns)
6. Scène complete (complete scene)
7. Lumière rythmique (rhythmic light)
8. Facteur de flare (lens flare)
9. Stroboscopique (stroboscopic)
10. Lumières dynamiques (dynamic lights)

The first section, *La luminosité* (brightness), contains blocks of intervals of seconds, for generating small brightness changes. The *glissando* operation allows these changes to be gradual. The double notes at the low register result in the absence of light, and to avoid problems with the pitch detector, pedal markings are used to indicate footswitch operation. The mapping range in this section is from C3 to A4.

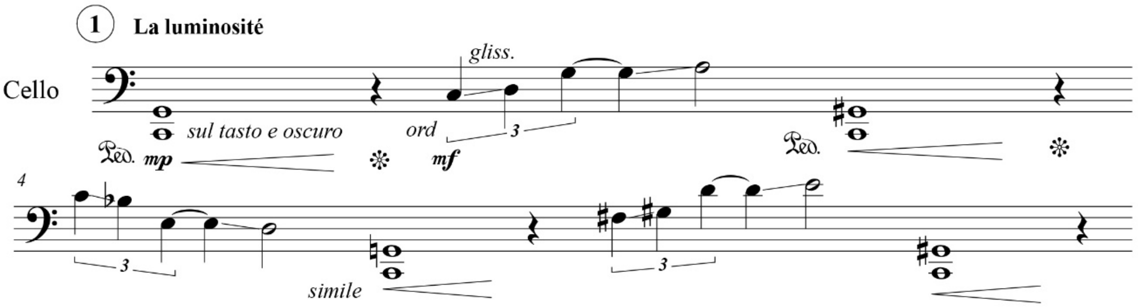



Figure 61. Future Lights: Section 1.

The second section, *Le faisceau lumineux* (the light beam), explores larger melodic leaps as the cello controls the angles of a light beam. The mapping range is of one octave, from G2 to G3.

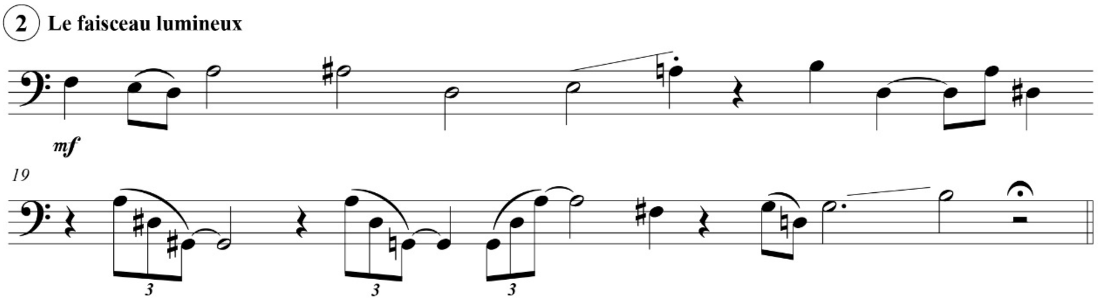



Figure 62. Future Lights: Section 2.

The third and fourth sections, *Mouvement d'etincelle* (spark motion) and *Jeu de profondeur* (depth game), aim to control the motion of several points of light. The glissando effect is combined with the motion parameter and some scalar melodic lines also create effective blends between sound and visuals. The high register double stops in Section 4 are performed with the footswitch to momentarily deactivate the pitch detector and trigger a "visual vibrato".

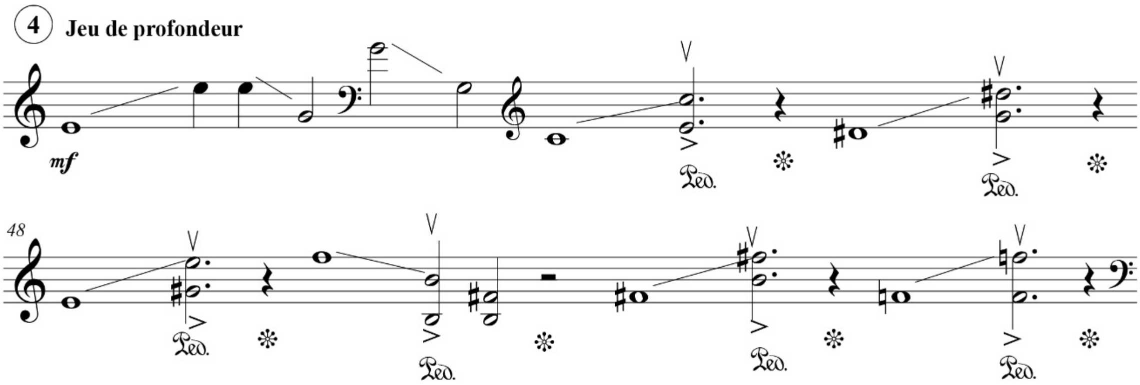


Figure 63. Future Lights: Section 4.

The fifth section, *La luminosité revient* (brightness returns), is similar to section 1 and provides some sense of traditional form, as it can be interpreted as a theme. The sixth section, *Scène complete* (complete scene), experiments with double stops going up melodically. This approach would not perform well with the pitch detector, but here it was mapped to the spectrum analyser. The use of polyphony provides a rich spectrum that is distributed to the brightness levels of five light sources. To make the source levels evident, a wide register was used, from C3 to an A4 harmonic (A5). This section ends with technical explorations on *glissandi*, moving from major second double stops with open strings.

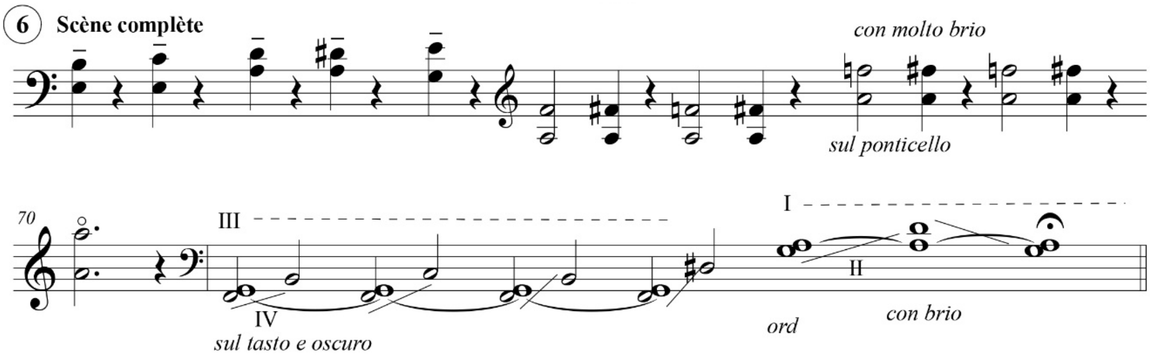



Figure 64. Future Lights: Section 6.

The seventh section, *Lumière rythmique* (rhythmic light), is a pizzicato section designed to trigger light motion in each stroke, through the amplitude detector threshold. It also explores the use of chords for cello.

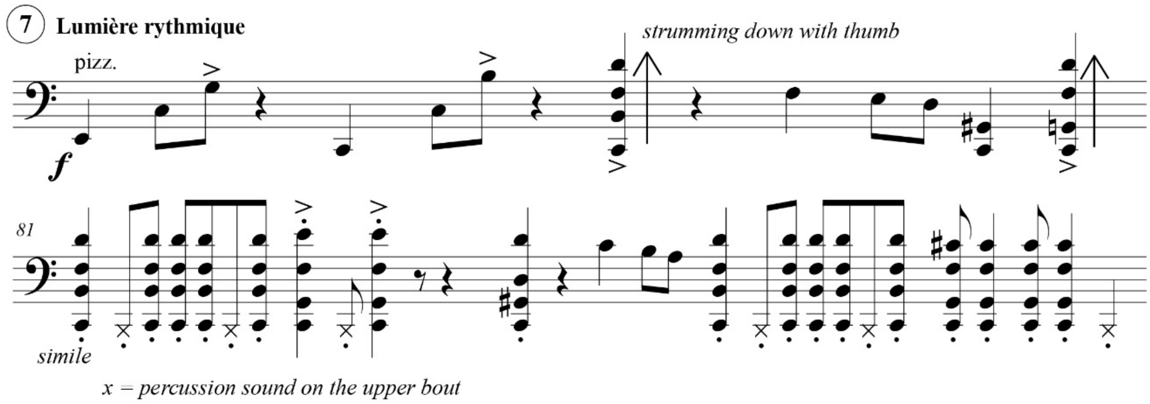


Figure 65. Future Lights: Section 7.

The eighth section, *Facteur de flare* (lens flare), utilises some larger melodic leaps. Although it employs the pitch detector, double stops are brought in a region where the higher note is mostly detected, thus not causing issues. A contrast between the high and the low register is invoked from bar 93, resulting in sharp changes in light intensity.

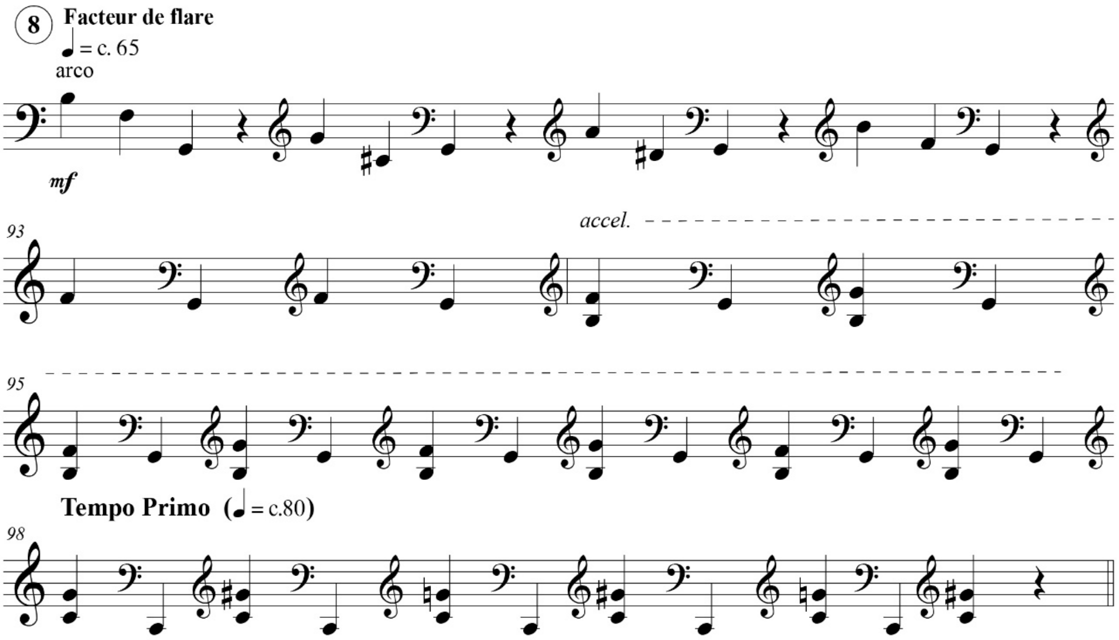


Figure 66. Future Lights: Section 8.

The nineth section, *Stroboscopique* (stroboscopic), is a short section dedicated to the use of tremolo in correspondence to a strobe effect.

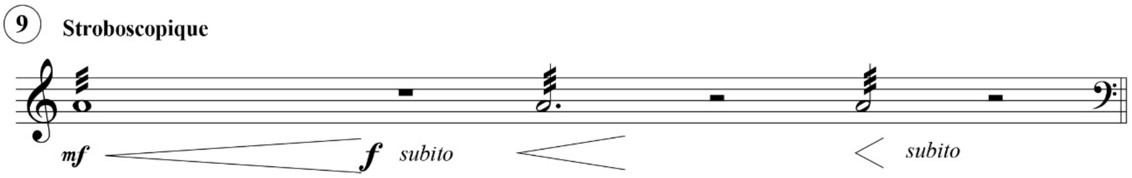



Figure 67. Future Lights: Section 9.

The tenth and final section, *Lumières dynamiques* (dynamic lights), presents a simple diatonic line, with emphasis on the dynamics. As a final experiment, the amplitude is tracked and mapped to the brightness level of the centre light. The composition concludes with a high pitch harmonic which triggers full luminance in the scene.

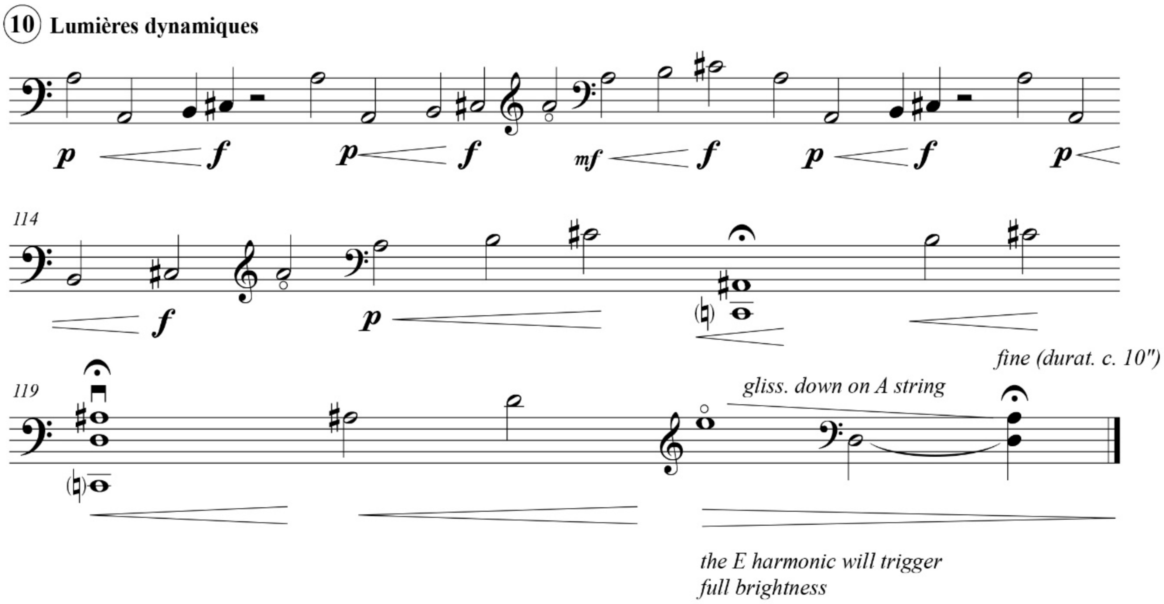
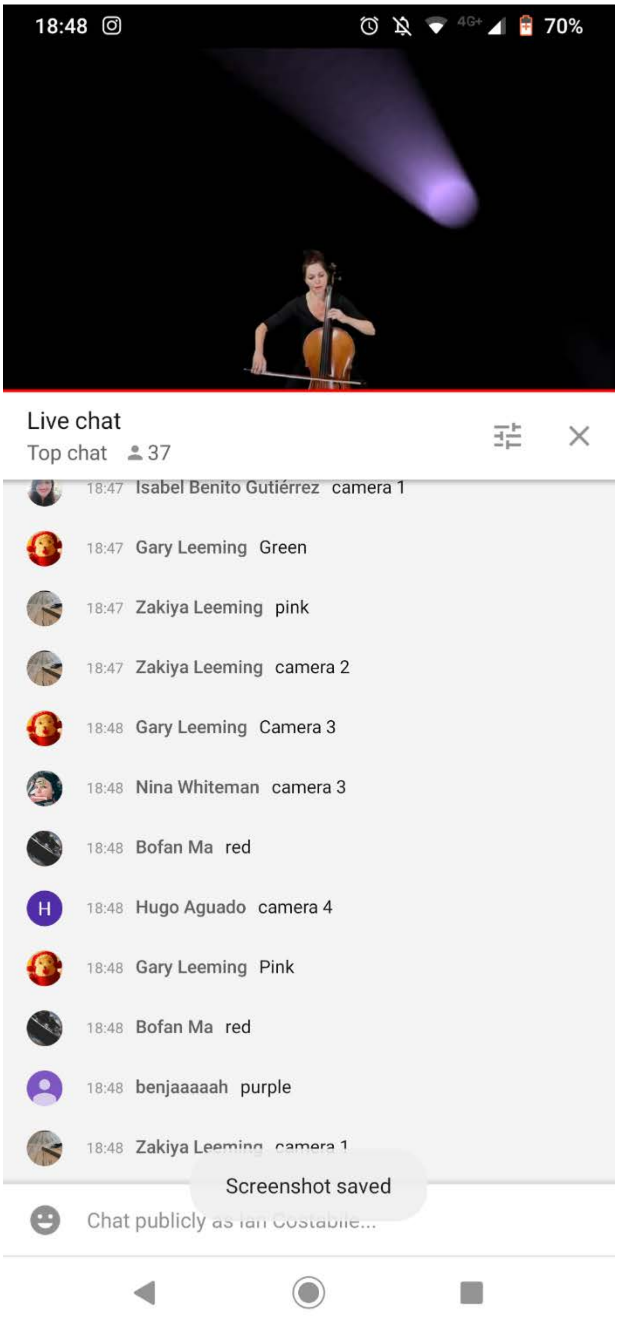



Figure 68. Future Lights Section 10.

5.5.5 Outcomes

The première performance of *Future Lights* on the 1st of September of 2020 attracted a live audience of about 40 people and received several "replay" views on YouTube. The audience engaged with the interactive system, which received input every second. A Q&A session after the concert was useful for receiving feedback and hearing the audience's thoughts on the technology used.



18:47 Isabel Benito Gutiérrez camera 1
18:47 Gary Leeming Green
18:47 Zakiya Leeming pink
18:47 Zakiya Leeming camera 2
18:48 Gary Leeming Camera 3
18:48 Nina Whiteman camera 3
18:48 Bofan Ma red
18:48 Hugo Aguado camera 4
18:48 Gary Leeming Pink
18:48 Bofan Ma red
18:48 benjaaaaah purple
18:48 Zakiya Leeming camera 1

Figure 69. Future Lights: Performance, mobile phone screenshot showing live chat interaction.

The virtual light systems using Max and OpenGL shaders proved to be efficient for facilitating interaction between instrument and live streaming. The shader codes available online for free were helpful for the quick implementation of visuals. The interface created for simulating lights in this project inspired another compositional investigation, *Intersidereal* (5.6), although this time utilising specific software for lighting design.

Light control in real-time with the cello was possible, although some sections did not operate well in the première performance in comparison to the rehearsals. This was due to last-minute changes in the instrument level which affected the calibration of the interface. The compositional strategy for dealing with the pitch detector issues, such as by using the footswitch and reserving polyphonic sections for other input detectors was positive.

The general latency time from receiving input from the audience and returning the visual output was of about 4 seconds. Streaming speed was provided through a fibre connection with an average of 20Mbps upload speed. Since the audience number was reasonable, this did not have major implications; however, a faster interaction would certainly enrich the project. As speed is expected to be improved in the near future with 5G and Wi-Fi6, the current latency could be reduced (Intel, n.d.). Other platforms that offer live interaction, such as Zoom, could also be explored.

5.6 Intersidereal

5.6.1 Concept

This suite of five short pieces for harp combines sound and light to portray the patterns and interactions of stars, constellations, and other embodiments of the universe. The first piece, *Lyra,* travels to the constellation of that name, which is symbolised by the ancient harp-like instrument, the lyre, and is thus depicted by the harp. The second piece, *Nebulae,* takes inspiration from the light diffusion of interstellar clouds of dust. The third, the *Minuet of Stars*, revives the old ternary dance in a modern design, where the tempo is conducted by light. This is followed by *Light Echoes,* embodying the phenomenon of echo as it occurs in space when flashes of lights reflect on interstellar dust. The closing piece, *Celestial,* illuminates the stage with flashes of light and explorations of the harp's harmonic flexibility.

Intersidereal employs the use of notated stage lighting for synchronising compositional events with lights in real-time. The aesthetics of the work combine the visual with the auditory, thus light operation works as an instrument alongside the harp.

Finally, as the composition was to be performed firstly through the internet, a virtual stage was developed using stage lighting design software (Capture 2020) in combination with OBS and Cycling '74's Max.

5.6.2 Objectives

This study aimed to explore a manual system for sound-light interaction. Whereas the previous study (*Future Lights*, 5.5) explored the use of automated or sensor-based interaction, this study uses a notated system, thus an operator is required for triggering light functions alongside the solo instrument. This is relevant to the research as it demonstrates other means for establishing sound-light interaction. Furthermore, adding an operator to perform alongside the harpist can provide human decision-making and subjective interpretation to the interaction, generating a different aesthetic experience.

This study relates to the score of *Prometheus* by Scriabin (see 2.2), where light colours are notated for performance, however, it aims to explore this concept further by adding other light effects such as sequential motion and flashes. As the project was developed throughout the 2020 pandemic, a virtual stage for performance was designed and this technology complements the study. Therefore, the following objectives were assigned:

1. Explore the use of score notation for stage lighting interaction.

2. Write music for the harp with simultaneous ideas for stage lighting.
3. Design a three-dimensional virtual stage and a video system for live performance.

5.6.3 Design

The score notation for stage lighting could be applied to any performance setting, however, for the online performance scheduled for April 2021, it was necessary to design an interactive virtual stage to simulate this interactivity. For this, a studio set with a green screen and three cameras was utilised to capture the performer's image. Three software programmes were used in parallel: OBS Studio, Cycling '74's Max and Capture 2020. For live operation, two devices were used, a two-octaves MIDI controller for light control, and a custom device, "dvControl", for camera and scene control.

Capture 2020 is a software commonly used by lighting designers as it features a 3D representation of performance stages. In this application, users can design custom stages, choose between a variety of fixtures and control them through common lighting console protocols. Although the software is commonly utilised for stage simulation, it is possible to use its graphics for compositing a live performance with chromakey techniques.

Light control interaction was planned through a MIDI controller device. However, as MIDI communication is not an option in Capture, Max was used for intermediating these actions. The Max external object *imp.artnet.controller* allows the use of the Art-Net protocol, which communicates with Capture via UDP. Thus, a Max patch was designed for establishing the links for MIDI communication.

OBS Studio was assigned for chromakeying the images, changing scenes and streaming/recording. Currently, OBS Studio only allows changes through keyboard shortcuts. In the previous study (Future Lights, 5.5), additional software was used to allow Max to send MIDI messages that were converted to OBS shortcuts. However, to avoid additional software and excessive CPU communication, a hardware device named *dvControl* was designed for camera operation.

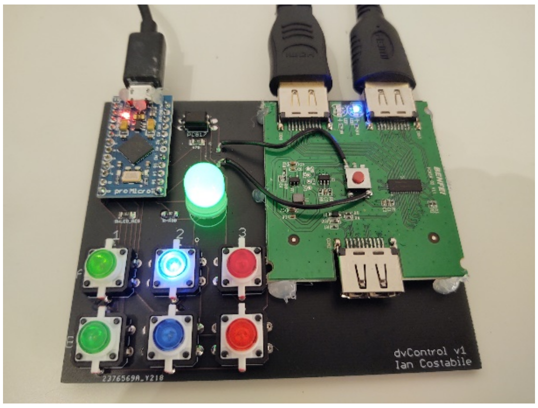


Figure 70. dvControl, custom-made device for controlling camera operation.

The *dvControl* device carries an Arduino Pro Micro, six LED pushbuttons, an RGB LED and an optocoupler. The Arduino Pro Micro is based on the ATmega32u4, which integrates USB communication and therefore allows keyboard simulation. Thus, at the same time it can trigger the keyboard shortcuts on OBS, it can send serial messages to Max, which consequently controls camera angle changes on Capture. The buttons allow an operator to select between six camera scenes. The optocoupler allows the microcontroller to trigger a digital HDMI switch, thus two cameras can share the same HDMI to USB adapter if necessary. The additional RGB LED is for indicating changes.

The structure of all technology used can be seen in Figure 71.

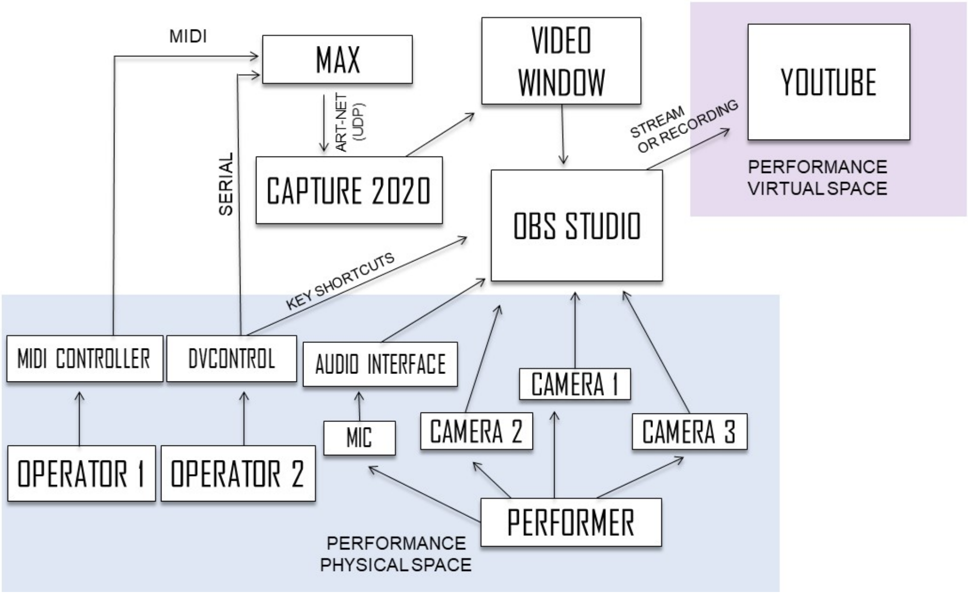


Figure 71. Intersidereal: Technology structure diagram

Virtual Stage Lighting Design

For the first four pieces, light is simply notated as “lights” without indications for positions (e.g., back lights, side lights, etc.). However, for the last piece, *Celestial*, position is indicated. As the project progressed, it seemed that grouping lights in sets and notating the score facilitated interaction, as giving a different function for each set allowed more efficiency. For instance, fixture automation such as colour changing and positioning takes time to process in Capture, thus if many functions are expected from the same fixture, operational conflicts may occur.

The fixtures were organised as:

1) 4x Back lights.
2) 5x Front lights.
3) 3x Left-side floor lights.
4) 3x Right-side floor lights.

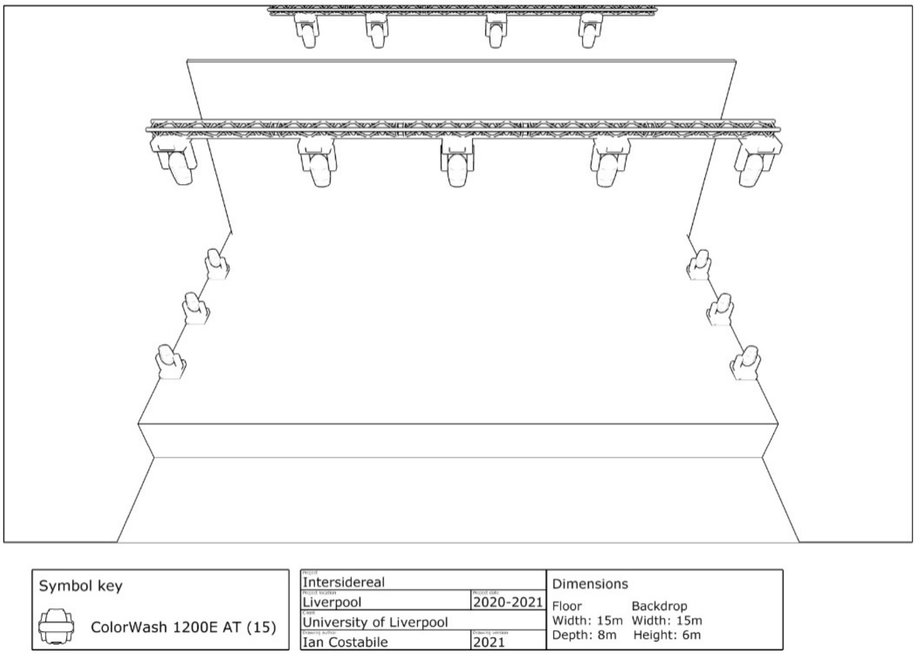


Figure 72. Intersidereal: Stage Plot

All the chosen fixtures are based on the *ColorWash 1200E* model, available in Capture 2020’s library. This specific model was selected as it allows motion (panning/tilting), zoom and colour control within 17 channels of communication.

For performance and real-time control, MIDI controllers were employed and connected to the Max patch. A variety of functions were assigned for each piece:

I Lyra: Front lights, 7 buttons (keys C to B) for dimmer control (on/off).

II Nebulae: Side floor lights, 11 buttons for colour control.

III Minuet of Stars: Front lights, 6 buttons for dimmer control (on/off).

IV Light Echoes: Side lights, 2 buttons for triggering flashing sequence (500ms delay between to sync with sound effect), 3 buttons for colour control.

V Celestial: All lights, 3 buttons for triggering light flashes and interrupting light motion, 1 button for triggering light motion (moving heads), 3 buttons for changing light colours.

5.6.4 Compositional Structure and Material

I – Lyra

The first piece of the suite was inspired by the constellation of Lyra, thus five stars from this constellation are represented by interaction from five spotlights. This piece was composed by using a "pattern" method, i.e., musical ideas that follow a similar melodic and rhythmic structure aimed to facilitate the implementation of light-sound interaction in computer programming, simplifying the light operator's performance. This would allow lighting presets to be used instead of requiring fast sound-light passages to be performed alongside the harpist, and it could also facilitate the implementation of the sound-light interaction into another media (e.g., *sound canvas*, see 5.7). These patterns are found in each bar and are defined by melodic and rhythmic motion. Six patterns were employed:

Pattern 1: Prelude
Pattern 2: Sulafat
Pattern 3: Sheliak
Pattern 4: Delta
Pattern 5: Zeta
Pattern 6: Vega

Except for the "prelude", each pattern takes the name of a star in the constellation of Lyra. Four of these patterns are also presented in their retrograde mode, allowing further variations. In addition, the *retrograde* idea was also taken as a metaphor for the *retrograde motion* of planets, which, as described in astronomy, is the observable path of a planet when it travels through the sky.

Considering its harmonic content, the introduction emphasises minor seconds and other harmonic material structured in quartal chords. The piece progresses to the tonality of F in the fourth degree of the Melodic Minor scale.

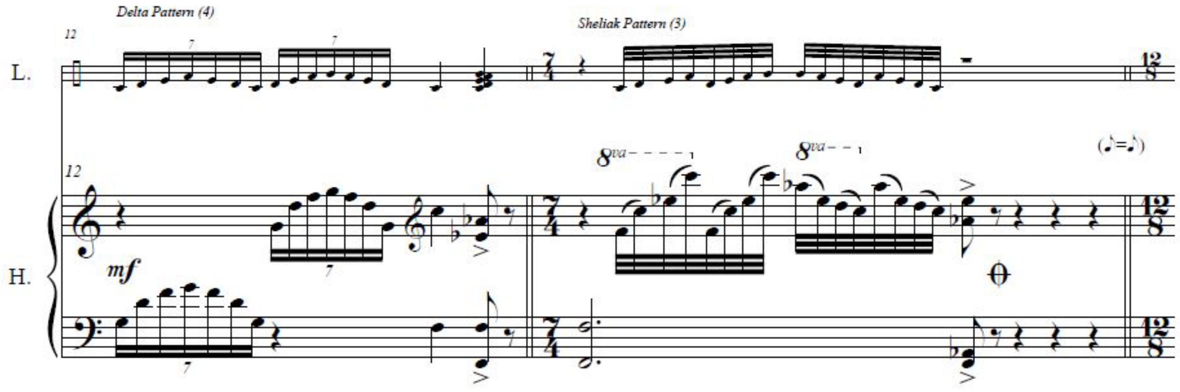



Figure 73. Lyra: Bars 12-13. Patterns for five spotlights are notated at the top stave.

II – Nebulae

This piece aims to represent the visual characteristics of nebulae images. Astronomical imaging from telescopes decodes infrared light through bright images, where clouds of a variety of gases can be differentiated by colour and texture. In this composition, notation for the lights' colours accompanies harmonic changes.

Texture is built by fast rhythms and *glissandi*, inspired by dense nebular clouds. The harmonic content of this piece begins with the notes C, D, F and G, which can be seen as a quartal chord, but sometimes presented as an F chord, comprised of added major second and major sixth, and absent of a third. Every five bars a note is flattened through the harp's pedal system. Thus, C becomes C♭ on bar 6, D becomes D♭ on bar 11, G becomes G♭ on bar 16, F becomes F♭ in bar 19. This motion allows chords to change gradually. Throughout all these changes, the E note is fixed as E sharp on the harp pedal, which allows the quartal sonority to continue during glissandos (except for the F♭ section). After these four notes become flattened, other sonorities are approached by further modulation.

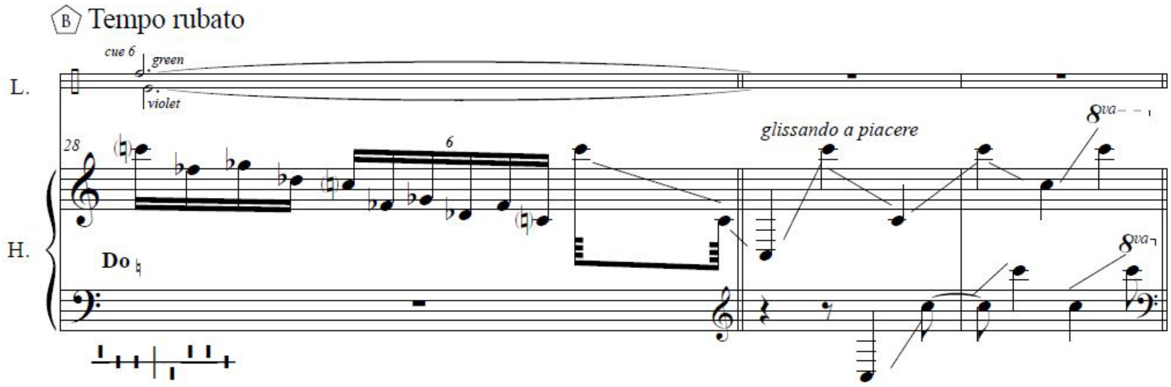



Figure 74. Nebulae: Bars 28-30. Light colours are notated at the top stave.

III – Minuet of Stars

The third piece takes the shape of a minuet, not completely conforming to the classical minuet, but following an A B A’ structure and keeping from beginning to end a ternary time signature and slow tempo, as if written for dance.

Lights begin before the harp, counting 4 bars. This was chosen to give exclusivity to the stage lights, allowing them to stand out as instruments. The harmony is taken from progressions within the G Major and E Minor scales, using suspended chords and borrowed chords from other keys.

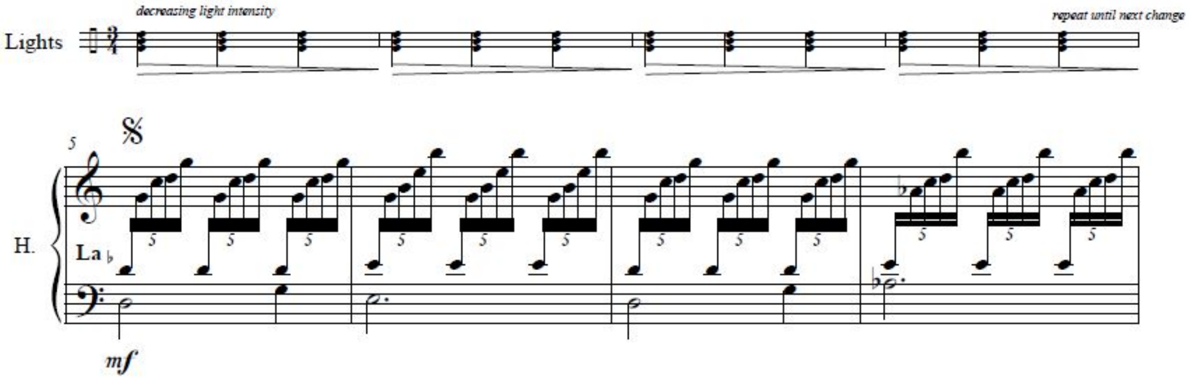


Figure 75. Minuet of Stars: Bars 1-4. Light intensity changes with the beat.

IV – Light Echoes

As echoes exist in sound, they also exist in light. They are not as noticeable as in sound, because of light’s superior travel speed. While sound reflection can be produced from a short distance, light bouncing off surfaces requires a planetary dimension to be observed. For example, light echoes of a star that exploded millions of years ago can still be traced, reflecting on dust particles in space. Using lasers, astronomers can also produce light echoes emitted from Earth to space, which allows them to calculate the distance of planets and stars (Cain, 2019).

This particular piece of the suite requires the harp sound to be processed with an “echo” or “feedback delay” effect. For avoiding sound feedback in the room, a contact (piezo) microphone can be used (e.g., Fishman SBT-HP).

At the top of the score, there is an indication that the echo effect should be set to 500ms, with at least 6 repeats. At 40BPM, each repetition of 500ms is equivalent to a quaver, thus the performer must take the effect’s pulsation as the beat. This is indicated as: “*echoes are your quavers...*”. In addition, spotlights are notated to flash and change intensity along with the echo effect.

The composition begins with the note D repeating in different octaves, suggesting reflections. Although most material in the piece is atonal, it moves through a progression of augmented chords that passes through an F major (bar 16), and eventually arrives in quartal arpeggios sustained by A on the bass.

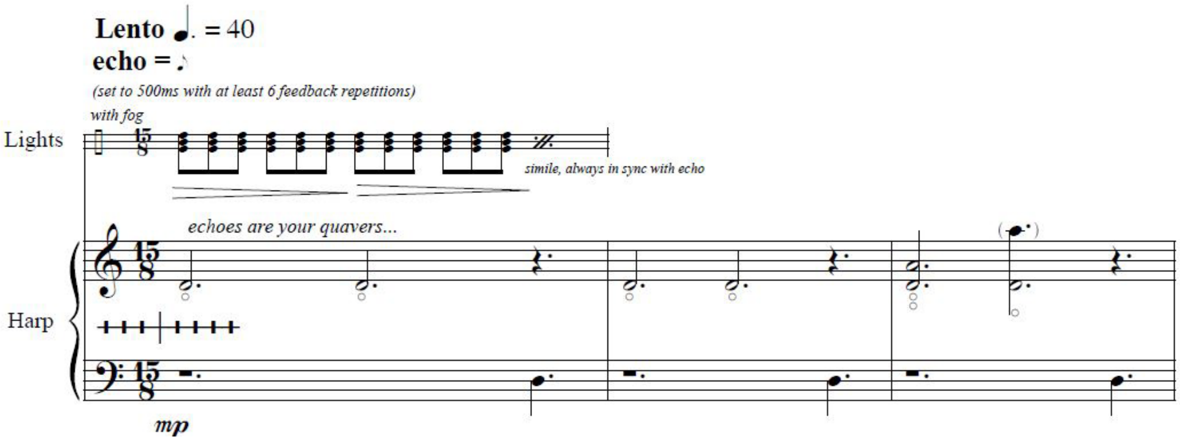



Figure 76. Light Echoes: Bars 1-3. Light intensity accompanies echo effect.

V– Celestial

The final piece aims to explore the interaction between rhythm and light flashes. Lights are notated in four lines, indicating different placements. Two sets of front lights, side lights and back lights. This allows spotlights to flash to and from different regions, generating different visual shapes. Accentuated rhythms are accompanied by light flashes from the front lights (e.g., bars 1-2), while continuous lines (e.g., bars 8-12) are accompanied by spotlight motion from the back lights. As in the second piece, the light colours change according to harmonic changes (from bar 44 onwards).

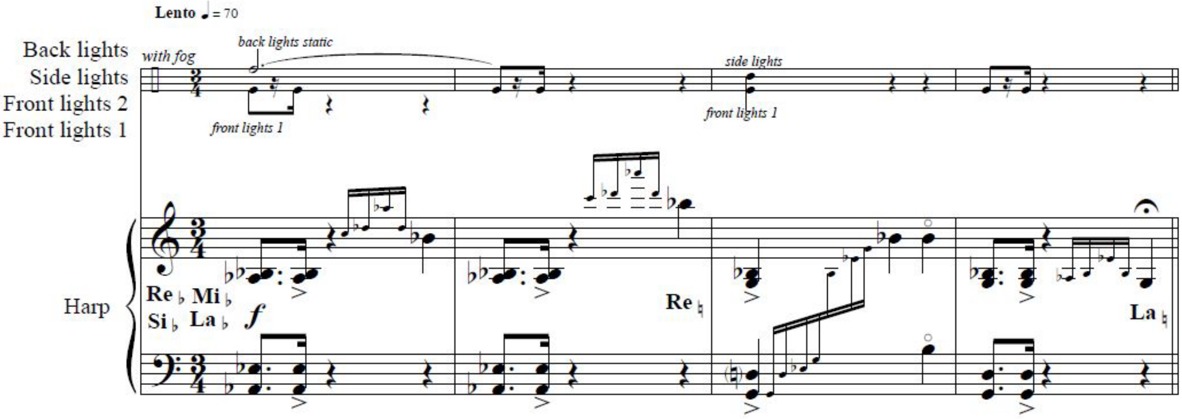



Figure 77. Celestial: Bars 1-4. Light flashes accompany rhythmic passages.

5.6.5 Outcomes

Intersidereal was performed by Bethan Griffiths on the 14th of April 2021, video processed through a green screen and live chromakey techniques. It was presented as a pre-recorded version on YouTube and as a live performance on Zoom. The pre-recorded version allowed video edition effects to create a better illusion of a virtual stage—e.g., camera zooming—and the light interactivity to be synchronised after recording. The Zoom performance included the light operator on stage, alongside the harpist.

Figure 78. Intersidereal: Pre-recorded Performance.

Figure 79. Intersidereal: Live performance on Zoom.

Having the light interaction notated and allowing it to be manually operated can avoid issues that may occur through automated/sensor-based systems; however, this type of interaction is also prone to flaws as human performance mistakes may occur (see mapping methods on 4.4.2). In addition, the human interaction between the light operator and the music performer can suggest a distinct aesthetic discourse, presenting a dialogue instead of a mechanised data system.

The combination of the three software utilised—OBS, Max and Capture—proved to be efficient. Capture, which is traditionally used for stage simulation, was explored with the function of a compositing stage for online performances and the results were satisfying, with no issues to note. In contrast to the previous experiment with chromakey on a cello in Future Lights (5.5), using chromakeying techniques with the harp in a home studio set posed a challenge, considering the gap between strings (which can expose the background), green colour reflection on strings, and the size of the instrument. Those issues affected the chromakey in some recorded scenes. Nevertheless, as it can be observed in many other scenes, with the correct placement of studio lights and colour adjustments it is possible to achieve the chromakey effect with a harp performer on the foreground.

Figure 80. Intersidereal: Performance set with green screen.

Finally, as the virtual backdrop utilised artworks by Jon Pountain, this study has suggested another possible collaboration between composers and visual artists in virtual settings.

PART III – Gallery Works and Installations

5.7 Sound Canvas

5.7.1 Concept

This project consists of the development of an alternative mixed-media format for the exhibition of sound art in galleries. Here the term ‘sound canvas’ is defined as a device that consists of a compact sound system within a defined surface, made to stand vertically on walls, resembling a traditional canvas painting. It can include other materials, such as printed or painted images, lights and sensors for interactivity. In addition, multiple loudspeakers can be placed on the surface, allowing multichannel sound applications.

Since it can combine multichannel sound and the use of lights, this project is valuable to this research as it contributes to other possible interactions between sound, light and space. The devices developed for this project also provide a basis for designing electronics for performances.

The first experiment of this kind, *Collage #1*, was a spatialisation study made in 2014 and exhibited at a sound art exhibition in Liverpool, UK. It consisted of a simple combination of four small stereo audio players and eight 1W loudspeakers, hidden behind a black painted canvas. It was a spatialisation experiment with recordings of different insects and birds. This study prompted further explorations through academic research. Therefore, the sound canvas project was the onset for this research, and it was continuously developed until its conclusion. Several pieces were produced and exhibited in conferences, wherein a variety of design models were explored alongside different types of technology. This media also allowed compositions (e.g., *Bi-dimensional,* 0) to be taken to a gallery context.

A sound canvas media offers a range of possibilities to the field of composition and sound art. It can be representative, as inclusive of recordings of soundscapes; performative, as inclusive of recordings of compositions; interactive, as it can offer control of sound placement and lights through the use of sensors; and conceptual, as other multisensory explorations can be achieved. Finally, this format can be an effective way to engage the visually impaired community with the experience of a traditional gallery narrative, where artworks are experienced in sequence as the audience freely walks through a museum or gallery.

5.7.2 Objectives

1. To design electronic interfaces for sound, light and user interaction through sensor technology.
2. To find solutions for compact battery-powered multichannel sound systems.
3. To experiment with different methods for exhibiting sound on walls.

5.7.3 Design

5.7.3.1 Multichannel Design and Software Integration

For developing compact and battery-powered multichannel systems that would allow sound to navigate between different loudspeakers different methods were explored:

Method 1: Microcontroller with asynchronous pairs of a stereo audio player module.

Method 2: Single-board computer running an Operating System (OS) and multichannel USB soundcard.

Method 3: Microcontroller with multichannel audio codec.

Method 4: Microcontroller with digital potentiometer and audio player module.

Method 1: Microcontroller with asynchronous pairs of a stereo audio player module.

The first method, consisting of asynchronous pairs of stereo audio player modules, is the simplest to implement. It can provide a multichannel system that is sufficient for concepts that do not require absolute channel synchronisation. For instance, *Collage #2* (Figure 81) combined four pairs of speakers in which sounds are panned in a circular fashion. The Seashore combined two pairs of speakers to simulate the sea waves breaking on the seashore. *Battistero, Voci della Terra e del Cielo*, a composition for soprano and tenor recorded at the Pisa Baptistery uses only one pair, split into recordings from two architectural levels to represent the full vertical panorama of the baptistery. All those artworks utilised combinations of the DFPlayer Mini module, which can communicate with a microcontroller (via Serial protocol) and can play MP3 files through an SD card (DFRobot, n.d.).

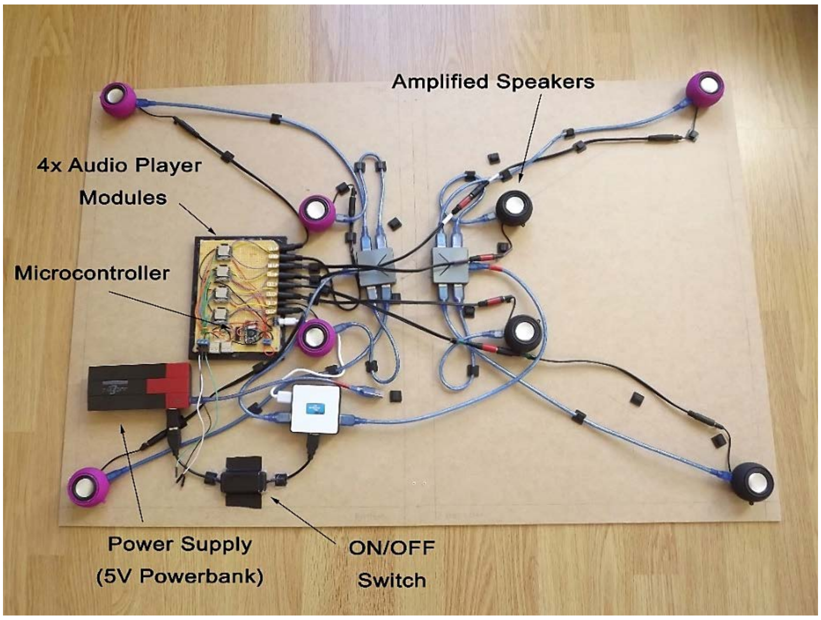


Figure 81. Collage #2: Internal circuitry (2017, 8-channel, 100x75cm).

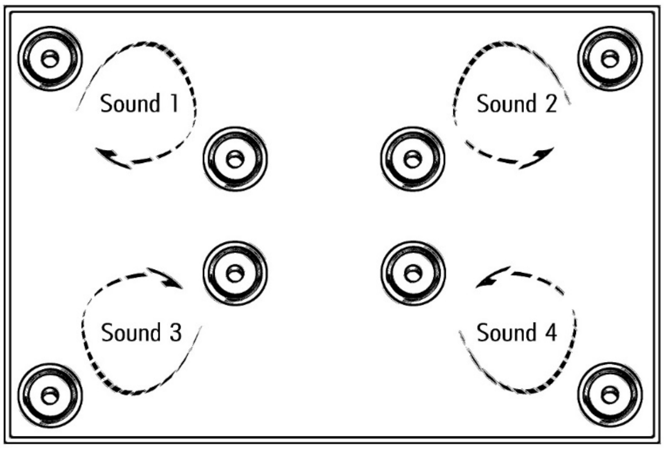


Figure 82. Collage #2: Representation of motion.

Method 2: Single-board computer running an Operating System (OS) and multichannel USB soundcard

The second method consisted of using audio software with common operating systems, capable of running on single board computers and outputting sound to a multichannel soundcard. Pure Data is a software efficient for multichannel audio control and capable of running on Debian through a Raspberry PI computer. Likewise, Cycling '74's Max offers the same functionality and it can run on Windows 10 through a PC-stick. This type of software presents advantages in terms of creating complex interactive systems or employing more sophisticated spatial techniques such as VBAP or Ambisonics.

Experiments were made with a Raspberry PI 2 and an Intel Compute Stick (1330 Mhz). The Raspberry PI was connected to a six-output audio interface, running Pure Data to route multiple audio files to different channels. Initial results showed that the boot loading time was long (about 15 seconds) and the system crashed occasionally.

A similar method was tested with the Intel Compute Stick operating Max, connected to a six-output audio interface and an Arduino Leonardo, which allowed pushbuttons to control the volume and other operations. By using the Ircam library Spat for Max, further spatialisation techniques could be experimented and this system resulted in a new artwork, a *sound canvas* based on the recordings of the compositional project *Bi-dimensional*, for flute, light and electronics (0). This system allowed control of different speakers and LED lights. In addition, through the integration of a microphone users could interact with the artwork — clapping hands triggered sounds in different places.

Despite achieving a certain level of functionality, using OS-based systems can be costly and might not be stable enough for long performance in exhibition settings. An OS has complications such as system crashes, slow boot loader, driver issues and particularly, high-power consumption. Considering all these negative points, this method was abandoned and controlling the circuitry through microcontroller units (MCUs) such as the Arduino platform was preferred.

Method 3: Microcontroller with multichannel audio codec.

The third method consisted of using a multichannel audio codec controlled by a microcontroller. This approach was initially tested with a codec module, the Tsunami Super WAV Trigger designed by Robertsonics and manufactured by SparkFun, which allows multichannel WAV files to be played through an SD card (SparkFun n.d.). This module includes a pre-programmed microcontroller (ATSAMS70N20 Cortex M7) and a multichannel audio codec (AK4618VQ).

This module, connected to six 1W speakers, another microcontroller and LED lights, was implemented in the *University Poster* project, exhibited at the PGR Showcase at the University of Liverpool in June 2017 (Figure 83/Figure 84).

The Tsunami Super WAV trigger module proved efficient for playing multichannel recordings, however, synchronising the spatial motion between speakers with LED lights was not straightforward. For instance, in the University Poster project, six speakers and 72 LEDs were placed in a hexagon shape. The spatial motion of the sound from one speaker to the next was synchronised with the light motion, through an Arduino board. To allow light to appear and disappear as the sound shifts, first it was required that the sound files were designed to spatialise between speakers in a defined BPM. By knowing the BPM of the spatialisation, the Arduino board was programmed to trigger the Tsunami module to play the recording and at the same time execute the LED motion, according to the same BPM. This method worked for this occasion, however, this module is limited for more complex interactions or live control of sound spatialisation, as this requires control over the main microcontroller (inbuilt in this module) which connects to the audio codec. Modifying the module is not a possibility as the software utilised in this board is not available for reprogramming it.

Another disadvantage of using the Tsunami Super WAV Trigger is the high cost of this module (as of January 2021, around 80 USD or 58 GBP).

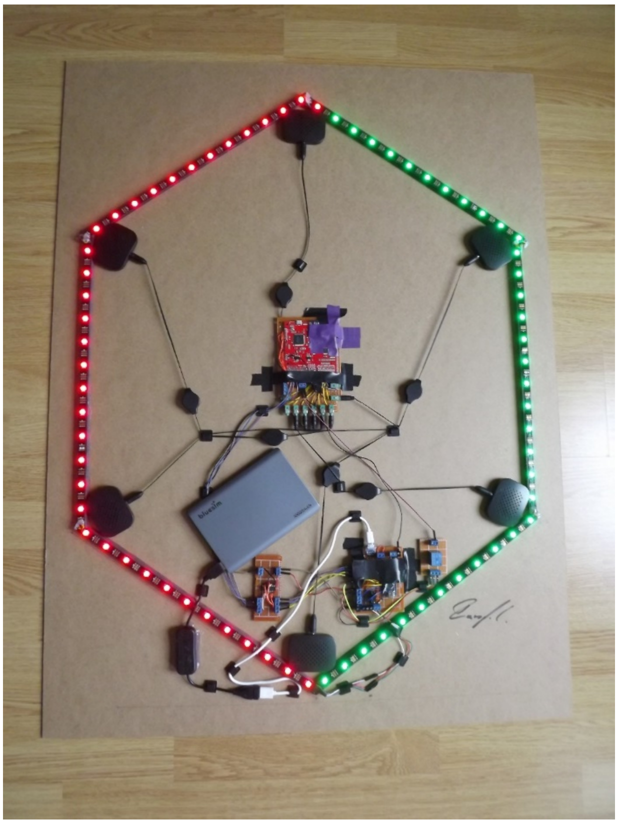


Figure 83. University Poster: Internal panel. Its multichannel system utilises the Tsunami Super WAV trigger.

Figure 84. University Poster (2017, 6-channel, 100x76cm).

The ideal scenario for this method is, therefore, to use a single and programmable microcontroller, which can access the audio files through an SD card, control the multichannel audio codec and the LED lights altogether. This was possible by combining a Teensy 4 microcontroller module (Stoffregen, 2019) with the multichannel audio codec CS42448 (Cirrus Logic, 2017). Similar to the Arduino platform, the Teensy offers open-source examples which include a library for the CS42448 (Stoffregen, 2017). A new circuit board was designed for allowing this system to work and utilised in a three-channel sound canvas, *Belt of Orion* (Figure 85). This same circuit inspired a commercial spatialiser prototype, developed through Sonalux (6.3).

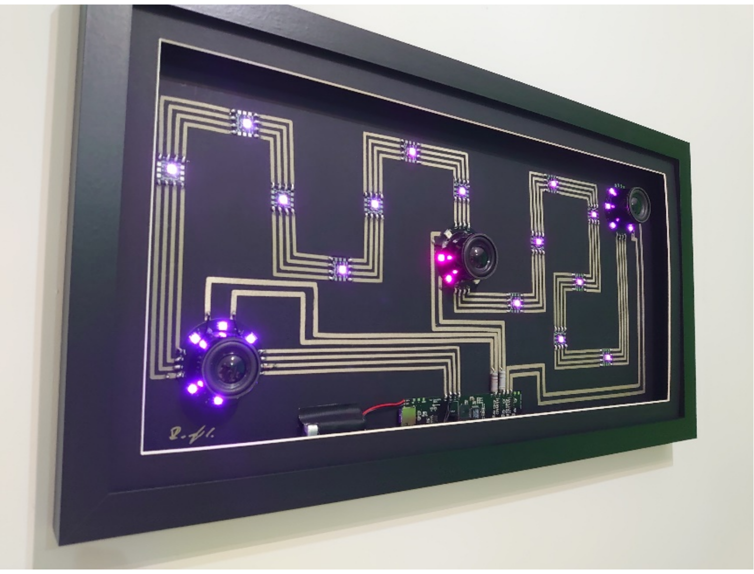


Figure 85. Belt of Orion (2021, 3 channels, 65x35cm).

Method 4: Microcontroller with digital potentiometer and audio player module.

The fourth method for multichannel control explored consisted of using a microcontroller and digital potentiometers. A digital potentiometer is an electronic component that operates as a potentiometer (a resistive device), allowing the sound level to be controlled digitally. Therefore, a microcontroller can instruct the digital pot to increase the volume in one speaker, while it decreases the volume in another speaker and generate sound spatialisation. In addition, different panning laws can be assigned for the numerical scale, allowing a variety of spatial design (see the amplitude panning studies on 4.3).

The digital potentiometers implemented were the MCP4241 (2-channel) and the AD5206 (6-channel), both communicate with microcontrollers via the SPI protocol (Microchip, 2008; Analog Devices, 2020).

The digital potentiometer method offers an efficient and unexpensive way of synchronising the panning motion of sound with LED lights. It was employed in *Sound Lines #2* (4-channel), *Lotus Sound* (6-channel) and *Lyra Constellation* (6-channel). Several iterations of circuit design for this method were produced, including iterations using Arduino boards (based on the ATmega328p) and more efficient microcontrollers, such as the ESP-WROOM-32 (Espressif Systems, 2019).

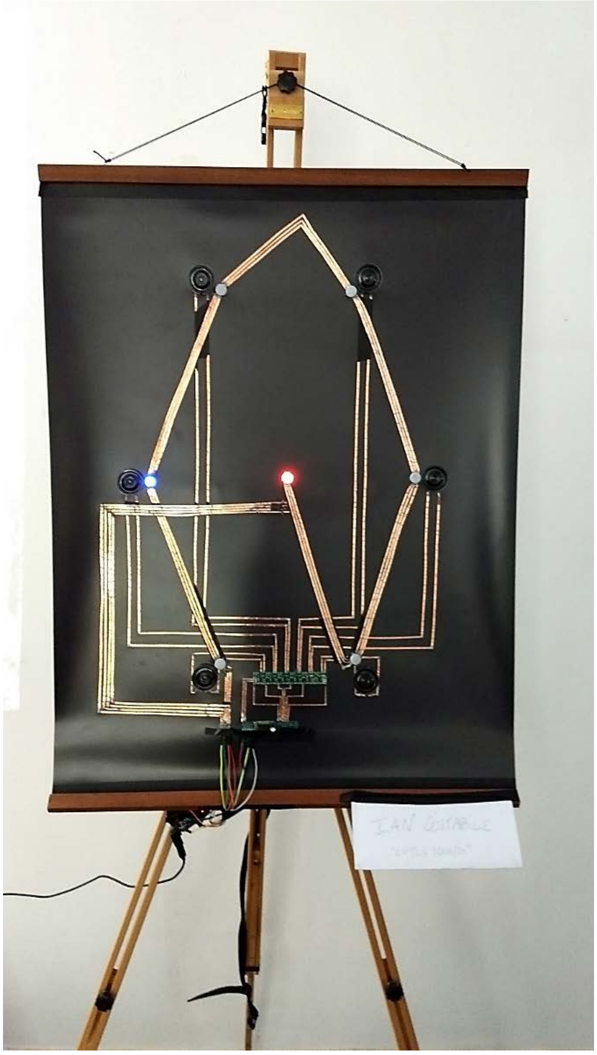


Figure 86. Lotus Sound: Multichannel system based on a 6 channel digital potentiometer.

5.7.3.2 Light and Sound Interaction

Some artworks produced included LED lights interacting with the multichannel outputs to visually indicate the sound motion between loudspeakers. They were:

- Bi-dimensional: 6x 5mm LEDs.
- University Poster: 72x WS2812B addressable LEDs.
- Sound Lines #1: 30x WS2812B addressable LEDs.
- Sound Lines #2: 30x WS2812B addressable LEDs.
- Lotus Sound: 7x WS2812B LEDs.
- Lyra Constellation: 20x WS1812B LEDs.
- Pulsar: RGB common LEDs.
- Belt of Orion: 32x HD107S LEDs.

Driving common LEDs with a simple 5V signal, as in *Bi-dimensional*, has no implications. However, the WS2812B presented difficulties as it added noise to audio signals. The WS2812B (Worldsemi, n.d.) is a common addressable RGB LED, allowing connections in series and thus facilitating the connection with the microcontroller (a single data output). However, when using the WS2812B, a certain level of noise was introduced in the circuits, which was picked up by the amplifiers. This was not so audible in most experiments as most compositions presented continuous soundwaves, such as in *Sound Lines #1* (single synthesised sound) or *Lotus Sound* (running water recording). However, when the same LEDs were used in *Lyra Constellation*, which integrates a composition for harp with silent bars, noise became evident. This issue is caused by Pulse Width Modulation (PWM), which is the common technique for dimming common LEDs or driving addressable LEDs. The PWM frequency of the WS2812B is around 400Hz, which is in the human hearing range and thus conflicted with the audio system.

Other experiments dimming common 5mm and 10mm RGB LEDs resulted in similar results. Driving these LEDs with an Arduino microcontroller (ATmega328p) by using the Arduino *analogWrite()* function, caused similar noise issues. In the ATmega328p, the standard PWM functions run at 490Hz for pins 3, 9, 10, 11 and at 980Hz for pins 5 and 6 (Arduino, 2020).

One solution[8] found for avoiding noise issues with PWM lights was to utilise another model of addressable LED, running above the human hearing range (above 20KHz), the HD107S (Rose Lighting, 2019) at 27KHz. This proved to work well in *Belt of Orion* (Figure 85). For common LEDs that require dimming directly from the ATmega328p microcontroller, a similar solution is to raise the standard PWM frequencies to frequencies above the human hearing range. This can be done by adding the following lines in the setup code:

For pins 3 and 11 at 31.3KHz: `TCCR2B = TCCR2B & B11111000 | B00000001;`
For pins 5 and 6 at 62.5KHz: `TCCR0B = TCCR0B & B11111000 | B00000001;`
For pins 9 and 10 at 31.3KHz: `TCCR1B = TCCR1B & B11111000 | B00000001;`

This method is effective and no audible noise can be heard. However, it is important to note that changing the PWM of pins 5 and 6 is not recommended, since it also affects the *delay()* and *millis()* functions. This leaves the ATmega328p with only 4 PWM pin options for working alongside sound circuits.

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[8] PWM audio noise is often a board layout issue, and it can also be eliminated by properly separating the digital and analogue circuit tracks. However, in compact systems, this may not be possible, thus raising the PWM frequency above the human hearing range may be an alternative solution.

5.7.3.3 Battery and Power Distribution

As many exhibition venues do not present electrical points in range, one aim was to integrate batteries and charging modules to all sound canvasses. In the beginning, power banks were utilised, and a micro-USB cable could be connected to the sound canvas' frame. As the project progressed, this was replaced by lithium batteries and a TP4056 charging module added to the electronic circuitry, and a connection could be made by USB-C.

5.7.3.4 Visual Design

Besides the electronic circuitry required to produce the sound canvasses, other aspects were proposed, such as fabric cover, volume buttons, USB charging integration and sensors for interactivity.

The first sound canvas design covered the circuits with fabric; thus, the visual aspect could be monochrome or a printed image. Different fabric materials were tested, and a polyester fabric seemed the most adequate for the project, since it can be stretched to the frame, it does not impede sound to pass through and it can diffuse light. Volume control, mode buttons and USB ports were added to the frame bars, allowing easy access for adjustments on the exhibition site.

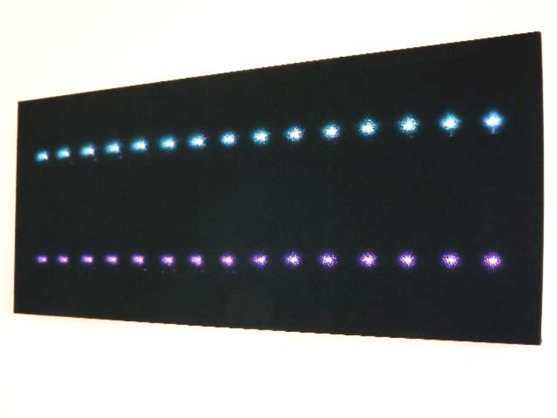

Figure 87. Design #1: Fabric cover. Sound Lines #2 (2017, 4-channel, 40.5x91cm).

The second sound canvas design was inspired by East Asian hanging scrolls. A scroll presents the advantage of portability, as the artwork can be made compact for conveyance. This approach required other techniques for construction. Whereas in the first design the circuitry and speakers glued to an MDF board, here the design presents a black magnetic sheet that can be rolled, and wires were replaced by copper tapes. The size of the components had also to be reduced and smaller loudspeakers were tested. The first prototype, *Lotus Sound* (Figure 86), was produced during the Visual Research Network residency in 2018. This artwork consists of six 3W speakers, seven LED lights and a proximity sensor. Another work using this design is

Lyra Constellation (Figure 88), created to play recordings of *Lyra* from the *Intersidereal* suite (5.6).

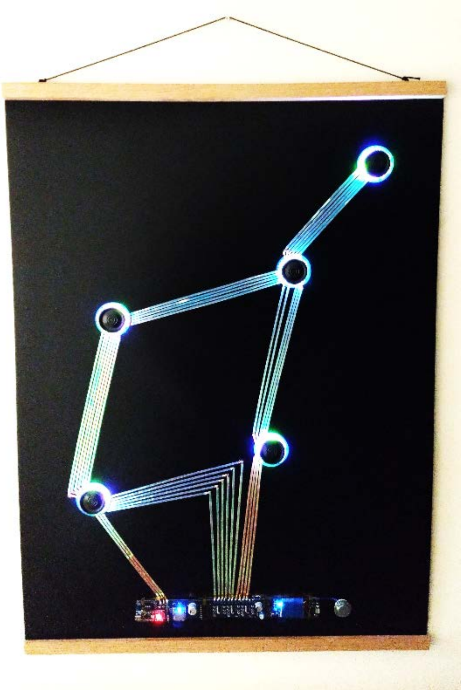

Figure 88. Design #2: Sound Scroll. Lyra Constellation (2019, 6-channel, 62x66cm).

In contrast to the advantages of the 'sound scroll' design mentioned above, the exposed artworks could be easily damaged and the action of rolling the canvas could affect solder joints. Therefore, a third design was elaborated, combining features from the first and second designs. The third design utilises a wooden frame but no fabric cover. The circuit is exposed and connected via copper fabric (cut with a digital cutting machine). Volume control, mode buttons and a USB-C charging port are provided under the frame. A laser sensor inbuilt on the circuit board allows the artwork to operate only when there is an audience in front of it. This allows multiple artworks to co-exist in the same exhibition room without interfering with each other. *Pulsar* (Figure 89), which presents a sound-light composition of three sections utilises this design model, as well as *Belt of Orion* (Figure 85).

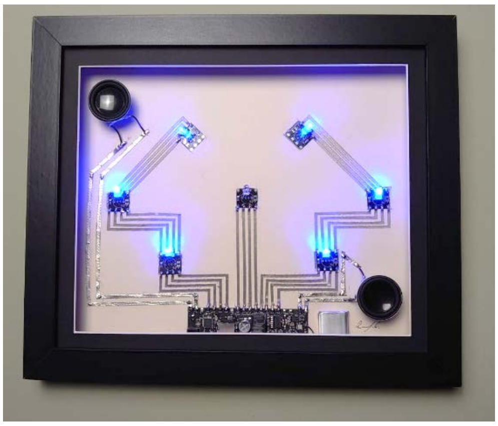

Figure 89. Design #3. Pulsar (2021, 2-Channel, 34.9x29.8cm).

5.7.4 Outcomes

The following sound canvasses[9] were produced throughout this research:

2021 – Belt of Orion (3-channel, 65x35cm)
2021 – Pulsar (2-channel, 34.9x29.8cm)
2019 – Sound Scroll: Lyra Constellation (6-channel, 62x66cm)
2018 – Sound Scroll: Lotus Sound (6-channel, 62x66cm)
2017 – Sound Lines #2 (4-channel, 30 LED lights, 30 sensors, 40.5x91cm)[10]
2017 – Sound Lines #1: The Earth's Orbit (2-channel, 30 LED lights, 80x30cm)[10]
2017 – Sounds from Bali & Sounds from Gili Meno (2-channel, 80x30cm)
2017 – University Poster (6-channel, 100x76cm)
2017 – Battistero, Voci della Terra e del Cielo (3-channel, 91x71cm)[10]
2017 – Bi-dimensional (6-channel, 100x35cm)
2017 – The Seashore (4-channel, 117×35.5cm)[10]
2017 – Spatial Poetry #2 (4-channel, 50x40cm)
2017 – Collage #2 (8-channel, 100x75cm)

Bi-dimensional was exhibited at the Threshold Festival 2017 in Liverpool, UK. *Sound Lines #1* and *Sound Lines #2* were exhibited in Dublin, at the Sounding Out the Space conference in Dublin, Ireland, in 2017. *University Poster* was exhibited at the PGR Showcase at the University of Liverpool in 2017 and won the Academic Jury Prize. *Lotus Sound* was exhibited

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[9] Video documentation of *Belt of Orion*, *Pulsar* and *Sound Lines #2* are included in the accompanying media.
[10] More information/images can be found in 6.1.

at the Visual Research Network conference in Manchester, UK, in 2018 and *Lyra Constellation* at the International Conference on New Music Concepts (ICNMC) in Treviso, Italy, in 2019.

This project also brought to light the *Sound Graffiti* project, which consists of a similar design, however, made for the outdoors and site-specific installations. Different installations were produced and exhibited in Liverpool and in Denmark. For instance, *Technogenesis* consists of a multichannel composition for six illuminated loudspeakers. The circuitry was based on the fourth method presented, in which microcontrollers control LED lights along with a digital potentiometer. The loudspeaker cases were produced with MDF wood and a laser cutter. This was exhibited in Hensingor and in Aalborg, outside the Musikkens Hus, as part of the RE:SOUND Media Arts Histories Conference in 2019.

5.8 PlatFORM: Composing Topologies

5.8.1 Concept

The sound installation *PlatFORM* was developed in collaboration with ECALab, a team of researchers who were exploring the use of ceramic material for architecture. Two walls of interactivity divided *PlatFORM* into two different concepts: *Composing Topologies* and *Interface Soundscapes*. *Composing Topologies* presented an interactive electronic composition designed by me, whereas *Interface Soundscapes* consisted of soundscape recordings by Dr Eduardo Coutinho, who supervised and collaborated in the project. This installation was showcased at the Tate Liverpool in 2018 as part of the TATE Exchange programme.

Composing Topologies contained 80 cones in total where 40 of them were sound/light reactive. Individual speaker circuitries were hidden inside the cones. 20 different pairs of sounds were assigned to each cone, plus a section of filtered pink noise (a process of random signals). Inbuilt proximity sensors allowed visitors to change the dynamics of the sounds and lights of each cone.

Figure 90. PlatFORM: Installation at the Tate Liverpool in September 2018.

5.8.2 Objectives

1. To design a multichannel sound system for 40 loudspeakers, including an interface for sound, light, and user interaction through sensor technology.
2. To find sound design methods for distributing a variety of sounds in a small space.

5.8.3 Design

Composition

Two compositional sections were planned. For the first section, 20 sounds were designed through digital synthesisers. All sounds were made to be continuous, suggesting an endless flow, and percussive sounds were looped with seamless techniques. The length of this section is 12 minutes.

The second section was designed with a pink noise generator and variations were produced through a high pass filter. The length of this section is 3 minutes.

This method of two sections resulted in a textural composition and allowed a greater interaction with the dynamics through proximity sensors, as well as an easier multichannel system to implement since there was no synchronisation of channels required.

Spatial Distribution

The sounds were distributed according to their timbre and frequency spectrum in order to allow better sound localisation. Bass sounds were set at the corners of the wall, and one high-frequency sound was positioned at the centre.

The same configuration of 20 sounds is mirrored for 40 cones, thus the wall was split in two segments (A-C and C-E in *Table 6*).

A				B				C				D				E			
1 bass		5 mid		9 perc			13 pipe		17 mid	17 mid					9 perc		5 mid		1 bass
	2 mid		6 mid	10 pipe		14 mid		18 mid			18 mid		14 mid		10 pipe	6 mid		2 mid	
		3 mid	7 mid		11 high	15 pipe		19 mid			19 mid		15 pipe	11 high		7 mid	3 mid		
4 bass		8 mid			12 wind		16 perc		20 low	20 low		16 perc		12 wind			8 mid		4 bass

Table 6. PlatFORM: Composing Topologies's sound distribution.

Circuit Design

The circuit design integrated an Arduino Nano (ATmega328p microcontroller), an RGB LED, a VL53L0X sensor, a DF Player module, a PAM8406 amplifier module and a 5W loudspeaker. All components were hand-soldered in stripboards. The DF Player module allowed MP3 files to be accessed from an SD card, sending the audio signal to the amplifier. The VL53L0X sensor is a laser-based range sensor that allows proximity to be measured. As visitors approximated their hands to the sensor, the microcontroller would gradually change the RGB LEDs and dynamically change the volume of the DF Player.

All boards were powered directly by the Arduino Nano's USB connector, connecting to a power hub and a 5V power supply. A single switch allowed all boards to start playing simultaneously.

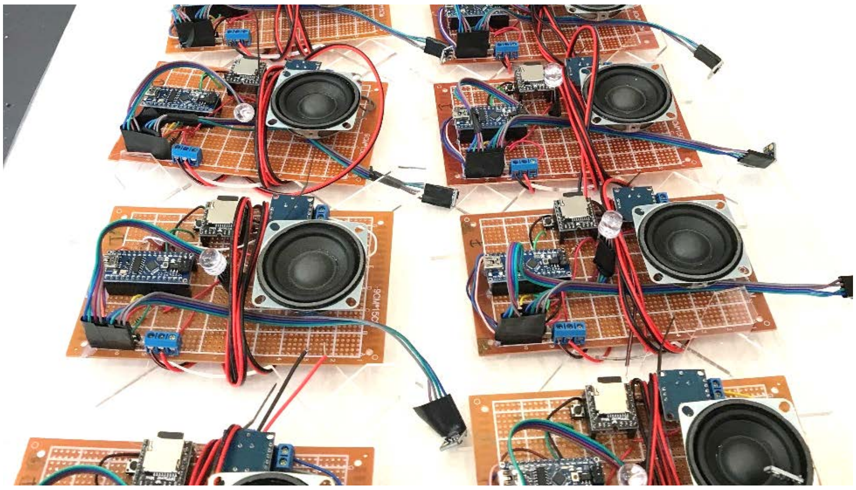

Figure 91. Circuit boards produced for the PlatFORM installation.

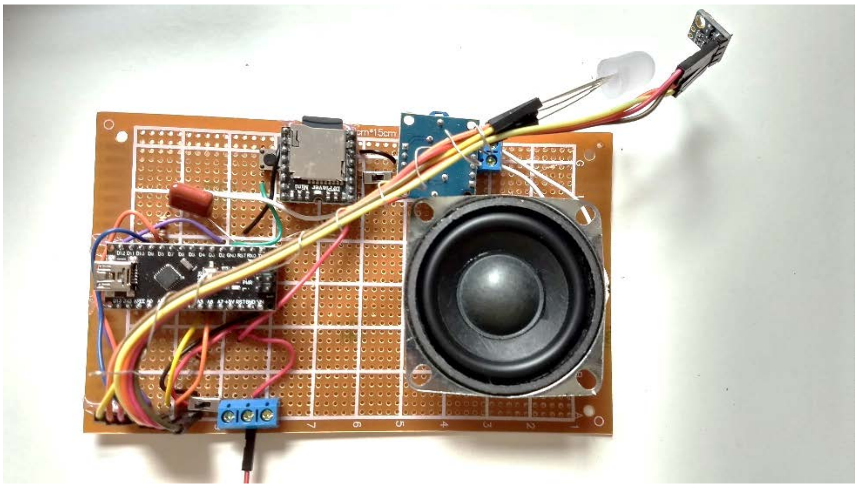

Figure 92. Circuit board produced for the PlatFORM installation.

5.8.4 Outcomes

The installation was showcased at the Tate Liverpool in September 2018, receiving hundreds of visitors. The light intensity and colour variation proved useful to guide the variations of sound dynamics as users approximated their hands to the cones.

The VL53L0X sensor proved to be efficient for this application due to its small size in comparison to ultrasonic sensors such as the HC-SR04, which would not be compatible to the size of ceramic cones.

The multichannel design utilised was asynchronous, thus a textural composition was made. This method was fundamental to avoid problems of synchrony; if the composition depended on synchronised events, a different multichannel system would be necessary, possibly requiring an expensive and more complex setup, such as using a 64-channel audio interface and a computer connected to microcontrollers (or a single microcontroller with multiplexers) to access the sensors and lights. Through this asynchronous method, each cone received a sound and electronic circuitry, requiring only an SD card for each board and the process of uploading the same code to each Arduino unit.

The first section allowed good sound localisation and dynamic interaction, as different frequency spectra and timbre were sufficiently spaced between cones. However, in the second section all sounds were composed of random signals (pink noise) and blended throughout the space. Even though random signals can offer better human localisation in comparison to common signals (see 4.2.2), this concept seems to fail when multiple noise frequencies are presented closely and simultaneously at the same space.

Figure 93. Visitors interacting with the PlatFORM installation at the Tate Liverpool.

6 Conclusion

The three key investigations presented before in the Introduction chapter were:

1. What new musical concepts can be found through the incorporation of spatial sound and light into compositions and installations?
2. How can spatial sound and light be controlled by performers and what types of interaction (mapping) can be created?
3. What new interfaces can be designed for spatial sound and light control?

Reflections and insights over those questions are presented here in the form of discussion and afterthoughts.

6.1 Conceptual Explorations through Multisensory and Kinetic Music

The union between light and space takes music to a multisensory level, where art is experienced through hearing, sight, and *kinaesthesia*——also known as *proprioception* or the *sense of space*. Hence, the kinetic properties of sound and light navigating through space also make music 'kinetic', with similar properties as of those found in kinetic sculptures. Different spatial arrangements and forms of motion can allow for the exploration of new concepts and representations.

The portfolio produced here has not focused on surround or three-dimensional spatial arrangements, but rather on spatial sound from a two-dimensional perspective. Since the *Sound Canvas* media allows small loudspeakers to be freely arranged in a two-dimensional space, several instances of kinetic geometry were experimented. For instance, concepts of lines (e.g., *Sound Lines #1* and *Sound Lines #2*), circles (e.g., *Pulsar*) and triangles (e.g., *Battistero*) were developed through experimentation.

Sound Lines #1 was a project that combined a back-and-forth line of light (a single row of LEDs) and sound between two channels. Similarly, *Sound Lines #2*[11] was composed of two rows of lines for a 4-channel system. In this canvas, interactive light sensors were implemented to allow the spectators to change angles between the two lines (sounds navigated horizontally and diagonally).

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[11] Video demonstration available in the accompanying media.

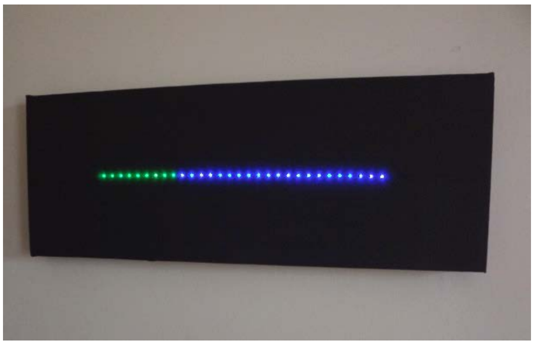

Figure 94. Sound Lines #1 (2017, 2-channel, 30 LED lights, 80x30cm).

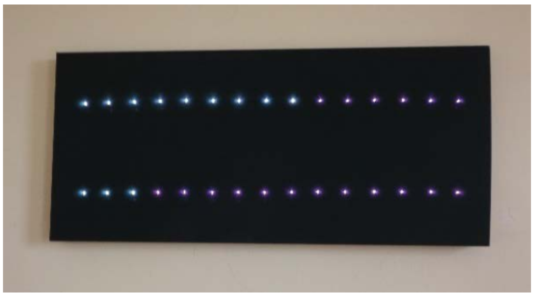

Figure 95. Sound Lines #2 (2017, 4-channel, 30 LED lights, 30 LDR sensors, 91x40.5cm).

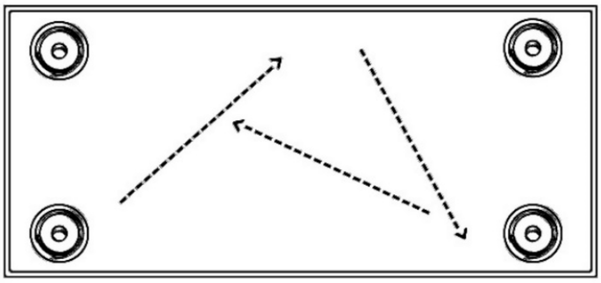

Figure 96. Sound Lines #2 (2017), representation of motion—sounds can navigate diagonally.

Spatial circular motion in two loudspeakers with light synchronisation was developed in *Pulsar*[12], which aimed to represent a rotating star. Although the kinetic arrangement is presented in a 2-D layout, the panning technique utilised creates a 3-D field of view as sound expands forward and contracts backwards while shifting horizontally, simulating the shape of a circle (see Circular Depth Study in 4.3).

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[12] Video demonstration available in the accompanying media.

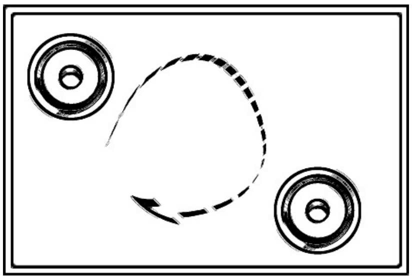

Figure 97. Pulsar (2021), representation of motion—circular depth effect.

The *Battistero* canvas reproduced a composition for tenor and soprano recorded at the Pisa Baptistery (which is known for its long reverberation time). The recording included channels from the top and ground levels of the baptistery, and the spatial arrangement was set to three speakers forming a triangular layout. The effect of sounds navigating upwards can be heard when in front of the artwork; in addition, this presents a curious finding concerning acoustic representation as it suggests how an acoustic space can be re-dimensioned to a compact frame—i.e., the ‘miniaturisation’ of an acoustic space.

Figure 98. Battistero (2017, 3-channel, 91x71cm).

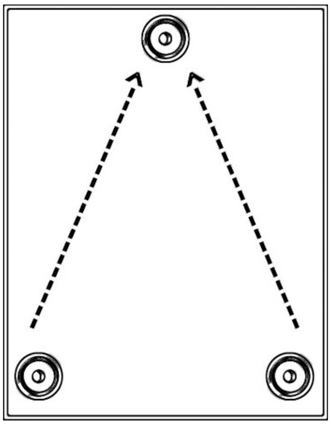

Figure 99. Battistero (2017), representation of motion.

Another instance of representation that can be made through a sound canvas can be heard in *The Seashore*, a four-channel simulation made of recordings of sea waves crashing on the shore, where waves crash in diagonal motion to the centre of the canvas.

Figure 100. The Seashore (2017, 4-channel, 117x35.5cm).

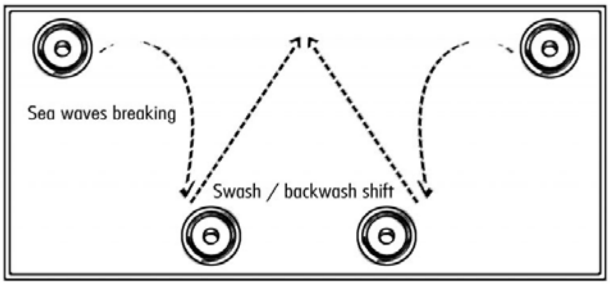

Figure 101. The Seashore (2017), representation of motion.

Regarding live performances, *Bi-dimensional*[13] created a dialogue between pitch and spatial sound, developing zig-zag gestures that also expand the audience's perception. *Lyra,* in *Intersidereal*[14], explored an arrangement that forms the shape of a constellation, where several melodic patterns of sound and light apply. In addition, the multisensory counterpoint of sound

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[13] Performance video available in the accompanying media.

[14] Performance video available in the accompanying media.

and light allows music to become more *playful*—i.e., the spectators might want to try to understand whether it is the *pitch* or the *dynamics* that are controlling the light *brightness*.

These practical studies of multisensory and kinetic music could be further developed, and new research could be proposed to engage ideas of kinetic music with aesthetic theorisations of space, such as by creating links with the studies of space developed by Rufolf Laban in the 20th Century (see Laban, 1980), which are well-known in the field of dance.

6.2 Interactivity in the Performance Space

Performances of spatial sound and light are often controlled by operators, but the progress of sensor technology in the last decades has been allowing performers to take control over those extra-musical aspects. As shown here, spatial sound can be controlled by hand gestures (*Syntony*, 5.1; *PlatFORM*, 5.8), the pitch of a flute (*Bi-dimensional*, 0) and similarly, light can be controlled by mallets (*Immanence*, 5.3) and sound signals (*Organoids*, 5.4; *Future Lights*, 5.5). Several other mapping parameters (see 4.4.1) could be employed.

The use of interactive elements can expand the performer's control, allowing space or light to become more fluid and organic. Interactive control can also be given to the audience. *Future Lights* (5.5) has shown a system where the audience could control light colours and other parameters via chat messages. This approach can be interesting, but it is more challenging to design, as a large audience can create excessive control and generate a chaotic environment. At a certain point, it can cross the frontiers from the art of listening to the art of play.

The use of virtual stages in *Future Lights* and *Intersidereal* was an option that emerged from the COVID-19 pandemic. The ideas were initially planned to be performed with DMX lights in a concert room. At the time (2020/2021), the UK restricted live concerts and a venue where lights and cameras could be set for recording was also not available. The solution was to explore a home setup with a green screen and simulate the use of stage lighting with virtual technology. Intersidereal was also planned to have multichannel sound and this could be simulated via headphones with binaural 3D simulation. However, I personally prefer to appreciate the effects of spatial sound without headphones and would not like to require the audience to wear them particularly for this event, thus this idea was discarded.

Nevertheless, the use of virtual stages showed another alternative exploration of the performance space. Furthermore, it provided innovative methods for virtual stage lighting control. It is possible that with advancements in technology virtual concerts of contemporary music will be further explored. Computer vision technology (i.e., deep learning architectures) already allows live compositing without the use of chromakey techniques, albeit presenting limitations.

6.3 Interface Design and Sonalux Ltd

This research has produced software and hardware interfaces. Through Cycling '74's Max, the following interfaces systems were created: performer-spatialisation system (*Syntony*, *Bi-dimensional*) and performer-light system (*Future Lights*, *Intersidereal*). In addition, Max was used for developing *Lyra Multichannel Player* (9.3), a multichannel audio player which was made available online for free use and was downloaded several times. *Immanence* and *Organoids*, along with other projects developed through the Transformation North West programme, have demonstrated hardware interfaces.

The development of those prototypes and the TNW programme's reflections on the use of design for industrial action inspired me to create a startup company, Sonalux Ltd. This initiative was supported by the Enterprise Fund from the University of Liverpool.

Through Sonalux, research continued in the form of designing interactive devices for musicians for production and commercialisation. The LED-reactive mallets utilised in Immanence inspired a guitar plectrum device called *MagicPick*. This operated similarly through a piezo disc, capable of flashing lights of different colours and running a metronome. Several months of work were dedicated to this device and commercialisation began in June 2021.

Figure 102. MagicPick by Sonalux Ltd.

Probably the greatest preoccupation in terms of design throughout the research was the development of a compact sound spatialiser to be used in the *Sound Canvas* project. The audio codec method (see 5.7.3) seemed the best option, however, the challenge of implementing a software library for this was very limiting.

When it was revealed to me that since 2017 the Teensy platform began providing support for TDM and the CS42448 (8-channel audio codec) this finally became possible (Stoffregen, 2017). This not only allowed me to explore further with mixed-media artworks, but also inspired to create a spatialiser through Sonalux, *Schaeffer 21*, named after Pierre Schaeffer (see *potentiomètre d'espace* in 2.1). This prototype device allows an operator to control 8-channel input (via SD card or 2-channel audio socket) to be projected into 8-channel output. It utilises constant power panning law (see 4.3) and the mapping of input-output can be easily seen through an LED matrix. A sequencer (autopan) is also integrated. This project is still under-development and might be commercialised in future.

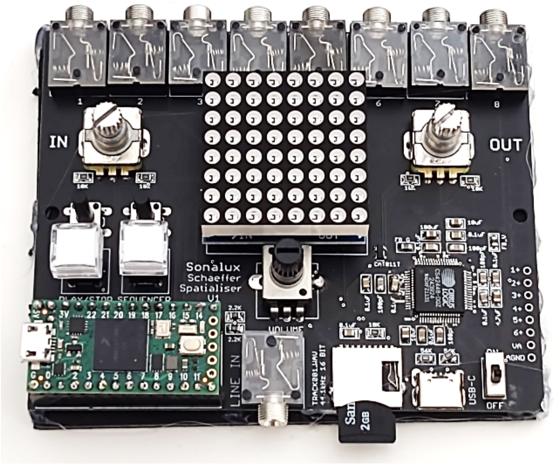

Figure 103. Schaeffer 21 prototype by Sonalux Ltd.

It is important to highlight that many of the technologies used in this research were relatively new[15], and some were released during the research process. For instance: ESP32 first released in 2016 (Espressif Systems, 2019), VLX53L0X in 2016 (STMicroelectronics, 2021a), VLX53L1X in 2018 (STMicroelectronics, 2021b), Teensy 4 in 2019 (Stoffregen, 2019) and HD107S in 2019 (Rose Lighting, 2019). This shows how the progress of technology continues to be significant for interactive art.

6.4 Aesthetic Remarks

This thesis has also expanded views from my previous master's degree dissertation, where I investigated the paths of originality in modern art. There I theorised four important paths:

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[15] This research was conducted between 2017 and 2021.

abstraction, appropriation, generation, and new technology usage, which were the main strategies used to sustain the modern discourse towards innovation.

Prior to this doctoral research, I worked with abstraction as my compositional strategies aimed to discard or highlight certain formal elements—for example, my works of ‘static music’ where temporal events were discarded to allow other formal elements to be highlighted. When I began working with the performance space, the focus was not abstraction but instead, appropriation. Making use of spatial sound and lighting allows other ways to engage with original ideas. Furthermore, works in this portfolio made use of new technology—e.g., sensors, virtual stage design and online interactivity, which supported a contemporary narrative. Generation was also explored through the *OPPO* project (9.1.2)—which in fact, the data collection process demonstrated could be expanded to become an ensemble composition.

Resuming the four-path theory mentioned above, I now suggest that music can find its paths to originality through additive or subtractive means; appropriation being additive and abstraction being subtractive. The other forms are concerns of process and creation, not defining the form—i.e., not how it sounds but how it is created. Today, I see many contemporary composers moving closer to the ideas of Helmut Lachenmann and denying all sorts of harmonic elements, aiming to subtract traditions even further. Conversely, music exploring the performance space, or music that incorporates multisensorial or other extramusical concepts, is created by additive means. This can also be seen in other types of compositions, such as works with video projections, live painting, theatrical elements, etc.

7 List of Tables and Figures

7.1 List of Tables

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8 Bibliography

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9 Appendix

9.1 Transformation North West Projects

9.1.1 AudioTrek

Concept

This project was developed through collaboration between members of the Transformation North West and Pulse Systems, a startup company based in Liverpool at the Sensor City hub, whose specialisation is in manufacturing sensor technology and IoT. The project aimed to produce a sensor-based assistive device prototype for people with visual impairments. It does not converge with the context of light and space for performance; however, it was relevant to this research as it concerns the design of audio devices with industry collaboration.

Technology for the visually impaired has been increasing with the development of digital technology. Sensor-based assistive devices can help people to do basic tasks, such as read, find a destination, recognise colours and go shopping. Some of these technologies include braille keyboards and e-books, text-to-speech functionalities in operational systems, smart canes with attached proximity sensors, smart watches with refreshable braille display, glasses for the colour blind, video call applications for smart phones and smart glasses.

Our goal was to develop a new assistive device integrating functions such as colour identification, long distance range finder, obstacle proximity, asset tag (e.g., QR code) and motion detection. This device could be useful for home use or supplied as an assistance device at cultural events. For example, in a gallery setting, it would be possible for the device to identify tags and orientated the user in space (e.g., exit, toilets, etc), and/or give information about an artwork on display.

Objectives

1. To design a prototype device using machine vision technology for converting visual data to speech and recorded sounds.
2. To implement algorithms with the OpenMV platform for colour identification, range finder, obstacle proximity, asset tag, motion detection and sound player.
3. To develop a 3D case for enclosing the hardware components and testing.

Design

Initially, we aimed to identify what modules for image recognition could be more effective. We tested two emerging technologies: JeVois (JeVois, n.d.) and OpenMV Cam M7 (OpenMV, n.d.). We concluded that although JeVois performed better in some situations (such as tags mode through Aruco), its cooler fan would be a nuisance for the purposes of a wearable device and solutions for working with the module without the cooler did not seem to be ideal. Furthermore, the connectivity of the OpenMV board facilitates the integration of other sensors (such as our range finder and the audio amplifier), making it a hardware preference.

The OpenMV supporting software (OpenMV IDE) comes with examples that are useful for creating the colour identification and asset tag functions. For the range finder, obstacle proximity and motion detection, the VL53L1X laser-ranging sensor was chosen. This sensor was a recent upgrade from the previous VL53L0X, with a higher ranging distance of 4 metres (STMicroelectronics, 2018). Playing sound was possible by connecting the OpenMV board's DAC with a TPA711 amplifier and a 18x13mm miniature speaker.

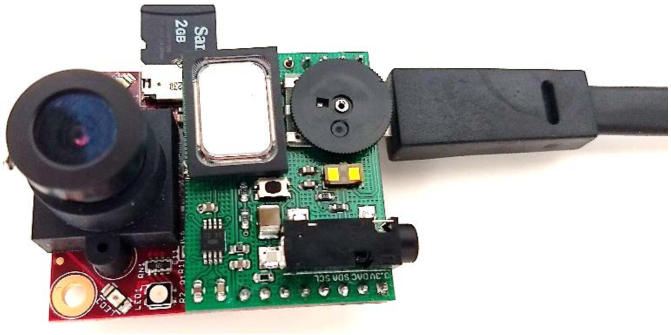

Figure 104. AudioTrek: Circuit board attached to OpenMV.

Outcomes

Pulse System supplied all components, produced the circuit board and reserved a workplace at Sensor City for further development of this project. Production took place from May to July 2018.

The prototype was finalised and integrated all expected functions. A speech database of WAV files containing numbers from 1 to 99, colours and units was produced, alongside codes for integrating the new VL53L1X sensor to the MicroPython language and the OpenMV IDE. This was valuable as R&D material for Pulse Systems, as it allowed them to integrate new technology into their products, therefore, also benefiting the purposes of the Transformation North West programme, which aims to create economic growth in the region.

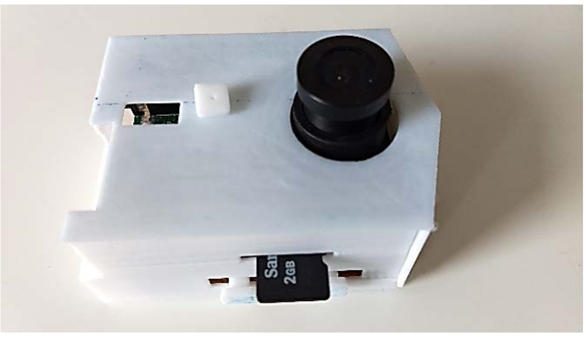

Figure 105. AudioTrek: Enclosed in a 3D printed case.

9.1.2 OPPO

Concept

The *OPPO* (Oscillating Personal Places Occurrences) project consisted of the design of sensor boxes and an Internet of Things (IoT) system that can collect data (light, temperature, humidity and motion) from a building and virtually translate it to a musical score. This project was a collaboration between members of the Transformation North West and two partner institutions. It was first implemented at Sensor City in 2019 and posteriorly implemented at two libraries in the University of Liverpool (Sidney Jones and Harold Cohen libraries) in 2020.

This project is relevant to this research as it concerns the design of electronics that can be used for sound, in addition to an investigation on how sensor data can be used for music composition. As an industry collaborative project, it complements the aims of the Transformation North West programme and was particularly useful for the research of Alexandros Kallegias, a TNW member researching the use of sensor data for architecture.

Objectives

1. To design a sensor box capable of collecting sensor data (light, temperature, humidity and motion) and to forward this data to an online database through Wi-Fi.
2. To create a virtual interface displaying the data collected every hour and automatically generate a corresponding music score.
3. To make the interface publicly available through physical and online methods.

Design

The *OPPO* boxes integrate a circuit board with four sensors for data collection: light (LDR), temperature (DHT22), humidity (DHT22) and motion detection (HC-SR04). The board was powered by USB and included an ESP32 development board based on the ESP-WROOM-32 microcontroller, which integrates Wi-Fi and allowed data to be easily transferred to other systems. An OLED display was integrated to show visitors the values of current data and a link to the project’s website. Finally, a 3D-printed case was designed to protect the circuits and to attach the device to the wall.

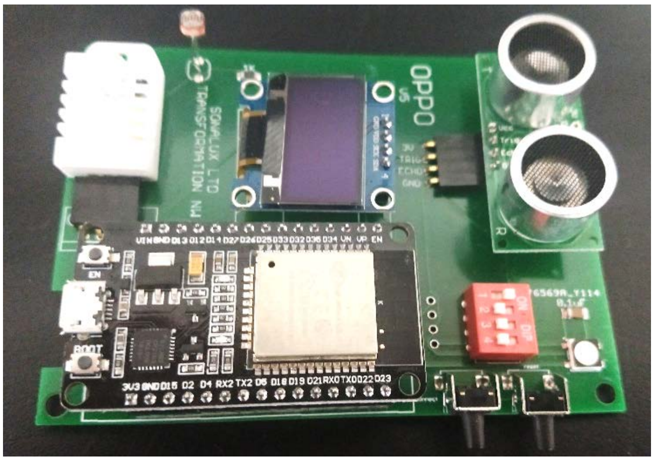

Figure 106. OPPO's circuit board.

Figure 107. OPPO device fixed on the wall.

The software was developed in two iterations. The first consisted of the microcontroller connecting to a computer, via UDP, to send real-time data to Cycling '74's Max. With a Max patch we could generate a live plot and score, with algorithms based in two timers to display 24 hours data as a 24-bars score. The first timer saved collected data every 5 minutes and the second timer created an average of this data every hour (Figure 108). The Max window (on presentation mode) was displayed in a monitor screen at the reception hall of the Sensor City building (Figure 109).

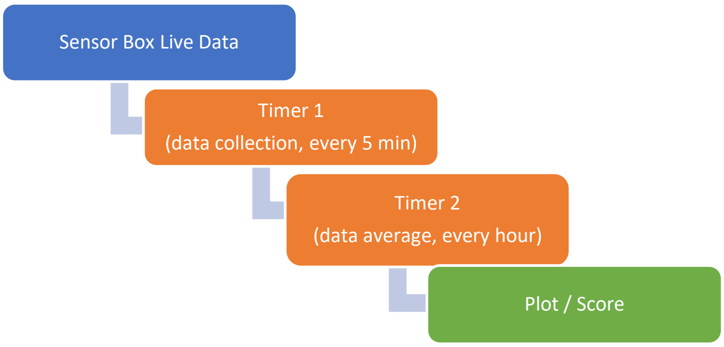

Figure 108. OPPO: 1st Iteration, data collection scheme.

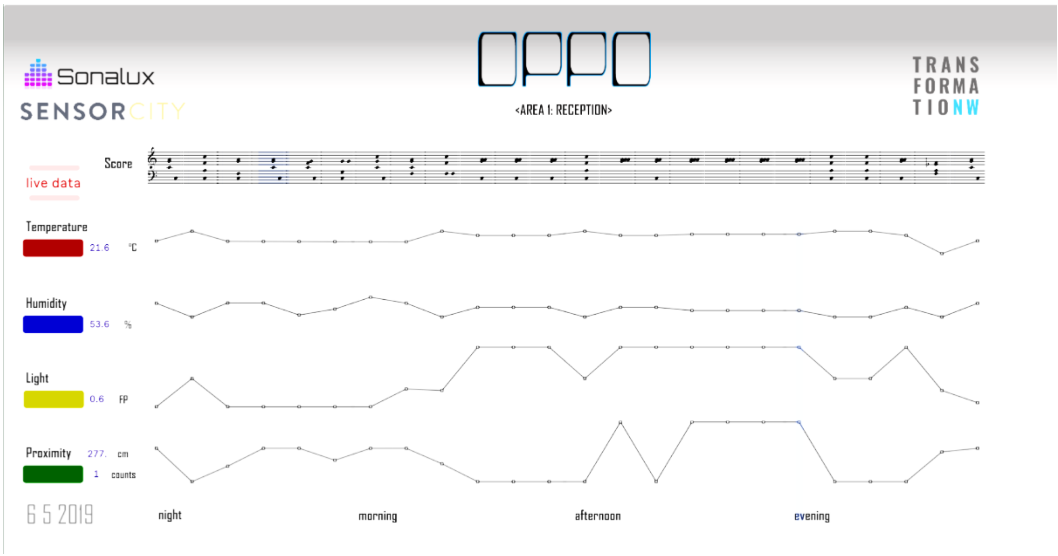

Figure 109. OPPO: 1st Iteration, monitor screen.

In this iteration, the process of sonification was mapping data from the four sensors in one room to four notes vertically, creating chords. The data values from 0. to 1. (Float numbers) corresponded to two octaves of a Dorian Pentatonic scale. Sounds were generated by connecting Max with external synthesisers (VST).

This system worked for a few days in the building. However, we realised Max was not the ideal platform due to excessive memory consumption, which caused occasional crashes, since it was operating 24 hours for several days. It also implied limitations in terms of updating the software and handling data. Therefore, we decided to experiment with another platform, and we began developing our second iteration with our own software, through JavaScript and MySQL. Instead UDP, the new microcontroller software was connecting via HTTP to a PHP file, containing instructions to upload the data to our MySQL database.

The sonification process was now produced through ABCJS, a JavaScript library that allows standard music notation to be rendered, along with MIDI playback functions. Thus, from the database we could locate data and generate the score and audio in a webpage.

The 24 hours of data was again translated to 24 bars, however, this time 4 different rooms corresponded to four different musical staves or instruments. Three sensors were mapped to beats in a triple meter (3/4) bar. Temperature corresponded to the note on the first beat. Humidity was positioned in the second beat and light in the third. The sensor values corresponded to variations in pitch within the range of two octaves in a Pentatonic scale.

The proximity counter, which was used for tracking activity in the rooms, operated differently. Instead having a fixed beat position and translate values to pitch mapping, it only added random notes in quavers, thus representing rhythmic activity.

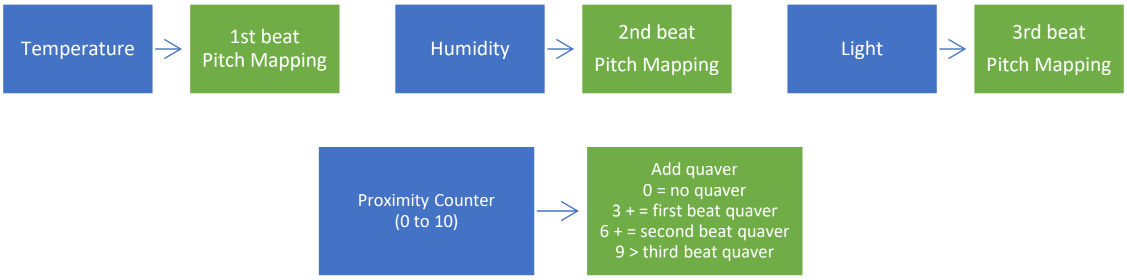

Figure 110. OPPO: 2nd iteration, data to sound mapping process.

Figure 111. OPPO: 2nd Iteration, web-operated version mapping 4 sensors from 4 rooms to a music score.

Outcomes

OPPO was implemented at Sensor City from June to August 2019 and at two libraries at the University of Liverpool from March 2020 to July 2021.

This project was presented in a paper at the Meetings of Minds conference organised by the NWCDTP in October 2019. This project demonstrated interdisciplinary practice and research between music and architecture. It demonstrated an efficient IoT model for collecting data through the ESP32 microcontroller and online sonification through the ABCJS library.

Figure 112. OPPO device and monitor screen at Sensor City.

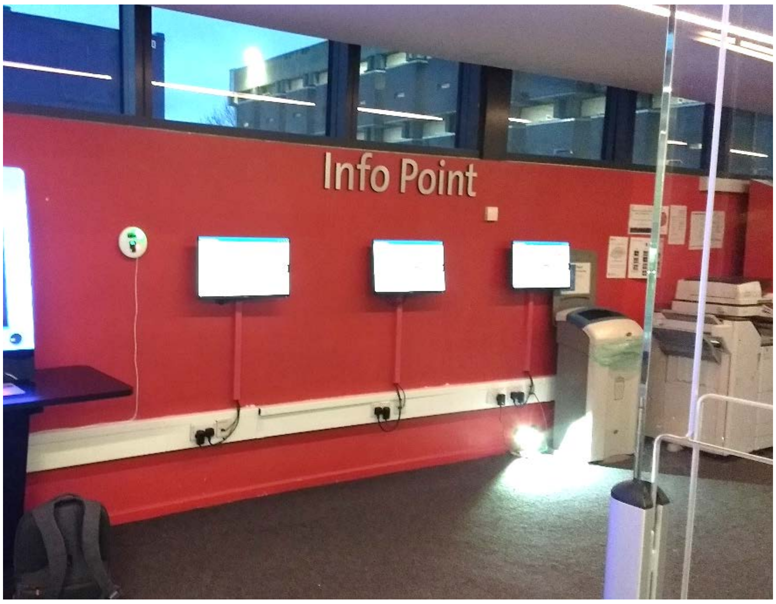

Figure 113. OPPO device at the Sidney Jones Library at the University of Liverpool.

9.2 Spectrum Designer

Figure 114. Spectrum Designer, additive synthesiser.

Spectrum Designer is an additive synthesiser software developed through Cycling '74’s Max. It allows users to see the spectrum they are creating, thus allowing certain frequencies to be selected in order to facilitate sound localisation.

9.3 Lyra Multichannel Player

Lyra Multichannel Player is a sound spatialiser developed through Cycling '74’s Max that supports up to 16 channels (I/O). Users can utilise a matrix to route channels as they like.

Figure 115. Lyra Multichannel Player, software for spatialisation.