Doctoral Thesis

Material, Embodied, and Spatial Relations in Augmented Reality

An Exploration of AR as a Medium for Musical Composition and Performance

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

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Colophon

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Declaration

I, Sam Bilbow, hereby declare that this thesis has not been and will not be, submitted in whole or in part to another university for the award of any other degree.

Brighton, UK,
20th November 2023

Sam Bilbow

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DEDICATION

for Hanna, Diane, George,

Otto, Celine and Momo

FOREWORD

Since beginning my academic journey eight years ago, the world – both its real and virtual counterparts – seems to have made tectonic shifts. There have been five conservative prime ministers here in the UK, and any reasonable discussion or policy around the most pressing matters facing the lives of people around the world – especially those who are most effected – has been all but absent. The COVID-19 pandemic, which began three months into this research, has only made it more painfully obvious that business-as-usual is not an option if we want a brighter and fairer future. Global supply-chains are hegemonic and fragile (Gomez et al., 2020), Western governments' health policy is naïve (Navarro, 2021), their climate policies purposefully inactive (Slawinski et al., 2017), leading to evermore demonstratively short-sighted mistreatment of nature and non-human animals (Monbiot, 2022). Only last week, the conservative government green-lit a £165 million deep coal mine in Cumbria, whose coal output could release 220 million tonnes of CO_2e downstream, over the course of the mine's 25 year lifetime (Grubb and Barrett in DLUHC, 2022, p. 252).

In the digital world – if it can at all be meaningfully separated from its physical counterpart any more – the last eight years have been equally tumultuous. From the Facebook / Cambridge Analytica scandal (Isaak and Hanna, 2018), to the rise of troll-farms threatening online and offline misinformation (Badawy et al., 2018); more and more, our understanding about the world and the people around us seems to be mediated by technology delivered by complicit or at the very least, apathetic mega-corporations. In spite of the convenience, interconnectedness and numerous other positives social networks have fostered, it has meant that in turn, the keys to our own behaviour are within reach of those with the capital to access and purchase it (Zuboff, 2019). This is compounded by the fact that centralised social networks also tend thrive on (Thorleifsson, 2022), amplify (Mathew et al., 2019), and promote (CCDH, 2022; ADL, 2022) – misogynistic, white-nationalist, antisemitic, homophobic, transphobic, and ableist hate speech, that has profound micro (individual), meso (group) and macro (societal) implications (Alkiviadou, 2019).

It was in front of this grey backdrop that I began the journey of a PhD four years ago. Despite (or due to) growing up with and around social media since the age of 11 – and economic, social, and cultural privilege notwithstanding – this backdrop has had a profoundly negative impact on my mental health since the COVID-19 started three months into this journey. More recently this effect was compounded by the threat of global nuclear war.

Acknowledgements

I therefore cannot express enough how much gratitude and appreciation I feel for my partner and fiancée Hanna for the amount of support she has so lovingly provided me over the last few years. She has made the tough days bearable, and the fun days memorable, I simply couldn't have done it without her. The past three months would not have been possible without the help of my therapist too; thank you Sarah. I would also like to thank my friends for encouraging me to take on this journey and providing me with more support than I think they know, especially Dan, Glory, Lauren, Joe, Dash, Chan, Nik, Harry, and the BeFries Team; and also those I've met along the way who have provided helpful ears, Fiona, Yaz, Colin, Katherine and Chris. Special thanks too to my family, close and extended who have provided me with motivation in times when I lacked the ability to conjure up my own.

The support from my main supervisors, Chris and Cécile has been invaluable, and I am indebted to their guidance over the past eight and three years respectively. Thanks also to Marianna, who provided me with insight on the role of multisensory technology at the start of the project, and Jamie, who took up the mantle in 2020, and has since offered insight into the cognitive neuroscience of perception.

I have also had the honour of sharing time and creative work with a number of Sussex faculty over the past eight years who are also very much deserving of thanks for their inspiring feedback on my work, specifically Thor Magnusson, Alice Eldridge, Dylan Beattie, Danny Bright, Alex Peverett, Joe Watson, Evelyn Ficarra, and Anil Seth. In addition, I have had the pleasure of meeting, making friends, and collaborating with, artists and researchers along the way. Thank you to Jon, Sissel, Steve, Dimitris, Max, Halldór and the Leverhulme DSP second cohort.

This research has made use of numerous free / libre open source software and hardware projects and communities, and wouldn't have been possible without the hard work and dedication of those employed at Leap Motion and Ultraleap: David Holz, Florian Maurer, Johnathon Selstad, Adam Hardwood, Pip Turner, and Alex Colgan; and Project North Star community maintainers: Noah Zerkin, ~j0ule, Damien Rompapas, Bryan Chris Brown, Juraj Vincur, Nova, and Moses to name but a few. Additionally, I have been made to feel welcome in several academic communities, including AudioMostly, TEI, and NIME, so thank you to the countless community organizers, and peer-reviewers that ensure that research in the sonic arts is a fun and welcoming endeavour. Thank you, lastly, to all of the pilot and study participants.

This doctoral research was funded by the Leverhulme Trust Doctoral Scholarship Programme: "Sensation and Perception to Awareness". Directed by Prof. Anil Seth, and Prof. Jamie Ward.

Publications and Texts

The following publications and texts are drawn from in parts of this thesis:

Chapter 3: Aesthetic Experience, Complex Music Systems, and the Metaverse

Bilbow, S., Kiefer, C. and Chevalier, C. (2021), The Value of Sound within a Multisensory Approach to AR in the Arts, *in* 'Proceedings of the Multisensory Augmented Reality Workshop', Interact, Italy, p. 8. Available at: https://dx.doi.org/10.5281/zenodo.7421488

Chapter 4: A DIY Approach to AR in the Sonic Arts

Bilbow, S. (2020*b*), 'Impact on human perception and expression, using augmented reality technology as a medium for computational art', *in* 'Internal Research Proposal' Available at: https://dx.doi.org/10.5281/zenodo.7421529

Bilbow, S. (2021*b*), Developing Multisensory Augmented Reality As A Medium For Computational Artists, *in* 'Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction', ACM, Salzburg Austria, pp. 1-7. Available at: https://dx.doi.org/10.1145/3430524.3443690

Chapter 5: Composing area~

Bilbow, S. (2021*a*), 'The area~ system: Exploring real and virtual environments through gestural ambisonics and audio augmented reality', *Sonic Scope: New Approaches to Audiovisual Culture* **2**. Available at: https://dx.doi.org/10.21428/66f840a4.b74711a8

Chapter 6: Evaluating polaris~

Bilbow, S. (2022*a*), Evaluating polaris~ - An Audiovisual Augmented Reality Experience Built on Open-Source Hardware and Software, *in* 'NIME 2022', New Interfaces for Musical Expression PubPub, The University of Auckland, New Zealand. Available at: https://dx.doi.org/10.21428/92fbeb44.8abb9ce6

THESIS SUMMARY

A DOCTORAL THESIS IN MUSIC TECHNOLOGIES BY SAM BILBOW

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SCHOOL OF MEDIA, ARTS AND HUMANITIES

DEPARTMENT OF MUSIC

Material, Embodied, and Spatial Relations in Augmented Reality

An Exploration of AR as a Medium for Musical Composition and Performance

It has been thirty years since the original definition of augmented reality (AR) as a technology used to 'augment the visual field of a user with information necessary in the performance of tasks'. In this first instance, it was developed with the purpose to 'improve the efficiency and quality of human workers in their performance of manufacturing activities' (Caudell and Mizell, 1992). Alongside subsequent decades of funding from the U.S. military-industrial complex (MIC), we have also seen the uptake and reappropriation of AR in creative fields, such as computational art, performance, design, and entertainment - these works often proposing do-it-yourself (DIY) and open-source approaches to their design.

Despite these developments, AR within sound-driven forms of art have been relatively under-explored. If an AR system can be thought of as one that can combine real and virtual multisensory processes, is interactive in real-time, and is registered in three dimensions (Azuma, 1997); why do we, thirty years on, witness the paradigmatic form of AR still being heavily biased (Billinghurst et al., 2015) towards it being a method of visual information overlay?

Standing in stark contrast to the currently unfolding and hyper-commercialised view of AR – as defined by the corporate 'Metaverse' – this thesis resituates AR as an artistic medium for the creation of interactive and expressive works by musicians and sound artists. It is guided primarily by the questions: *'What are AR's affordances as an artistic medium, the resultant experience for participants and audiences (or 'immersants') in these experiences, and what might a future corpus of AR digital music instruments look, sound, and feel like?'*

To address these questions, this practice-based of research takes a *DIY Approach to Sound ARt*, arguing that, as an medium that combines real and virtual multisensory processes, it must explored with a sensory-process agnostic approach – that is, to approach AR as more than mere visual information overlay – instead as 'real-time computationally mediated perception' (Chevalier and Kiefer, 2020). This has involved making and hacking technology as an necessary aesthetic and political stance against commercial AR technologies in their typical form.

Three sound augmented reality art (ARt) experiences are outlined, and embody the majority of the practical contribution of this thesis: *area~*, *polaris~*, and *polygons~*. In discussing the results of these three study chapters, theoretical propositions are made: *'augmented materiality'*, *'augmented embodiment'*, and *'augmented space'*, that have implications for the use of AR as a sonic medium. Moreover, out of the iterated design of the AR experiences, their study, evaluation, and discussion, three 'design patterns' for those in the field interested in reproducing or developing similar sound ARt have been developed: *Designing for Rich AR Experience*, *Consideration of the AR Instrument*, and *Role of the Virtual in the AR Environment*.

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Working Definitions

4EC **4E Cognition** . . . 6

A theory of embodied cognition opposed to the standard cognitivist model; it states that cognition ought to be conceptualised as being an *embodied*, *embedded*, *enacted*, and *extended* process. Analagous in this thesis with 'enactivism', or 'enactivist' approaches

ACCA **Attenborough Centre For The Creative Arts** . . . 102

A performance and events venue at the University of Sussex

AAR **Audio Augmented Reality** . . . 7

AR focused on sound-driven approaches to designing and displaying media experiences

A/V **Audiovisual** . . . 7

Typically a media format that uses visual and auditory display

AR **Augmented Reality** . . . 3

A technology, system, or process that facilitates real-time computationally mediated perception (Chevalier and Kiefer, 2020)

ARt **Augmented Reality Art** . . . 6

Art that uses AR as its medium of expression (Rhodes, 2018)

ABD **Autobiographical Design** . . . 7

A research method that involves building, testing, and evaluating systems through documented self-use and iteration (Neustaedter and Sengers, 2012)

BPF **Band-pass Filter** 70

A type of filter that allows specific frequencies, or ‘bands’ through, but attenuates other frequencies

CRT **Cathode Ray Tube** 11

Typically used as short hand for ‘CRT display’: a type of technology that that uses a vacuum tube and cathode rays to output images on fluorescent screens. Developed in the early-mid 20th century.

DARPA **Defense Advanced Research Projects Agency** 11

A U.S. federal government agency recognised for its contribution to large amounts of modern technology, typically for military use, such as weather satellites, GPS, drones, stealth technology, voice interfaces, the personal computer and the internet (The Economist, 2021)

DMI **Digital Musical Instrument** 4

A type of musical instrument that makes use of digital software and hardware.

DIY **Do it-yourself** 3

A design philosophy that promotes creating systems from the ground up, often associated with the Maker movement.

F/LOSS **Free / Libre Open-source Software** 7

A philosophy that promotes the development and disessemination of software in an ‘open’ way that allows others to contribute freely to the ‘source’ code. Typically free can have two meanings: free as in monetarily free, and free as in the liberty to use freely in any way. Thus ‘free / libre’ is used as a distinction for those projects that do not adhere to both terms.

HMD **Head-mounted Display** 12

A type of display technology (typically visual) worn on the head, that provides output from a computer directly (e.g., through lenses) or indirectly (e.g., via mirrors) to the eyes. One of the main forms of AR and VR display.

HRTF **Head-related Transfer Function** 18

A mathetmatical model that takes into consideration the shape and phisiology of a human head, auditory subsystem, and torso. It can be applied to a sound in order to give the illusion of it originating from a three-dimensional position in space. (Blauert, 1969, 1996)

HUD **Heads-up Display** 12

A type of (typically visual) display technology that usually provides contextually relevant information to a user. Often but not necessarily via an HMD

HCI **Human-computer Interaction** 6

A field of science based on the design and evaluation of computational systems that provide human interaction

IMU **Inertial Measurement Unit** 65

A small device that typically uses sensor fusion to provide accurate readings of acceleration and orientation

ICST **Institute for Computer Music and Sound Technology** 71

A research institute at Zurich University of the Arts (ZHdK), focused on computational approaches to music composition, performance, and spatial display

IRCAM **Institute for Research and Coordination in Acoustics Music** 67

A research institute at Centre Pompidou in Paris, France, focusing on approaches to sound in avant-garde and experimental electo-acoustic music

LMC **Leap Motion Controller** 65

A hand tracking device that uses infrared sensing to detect individual finger joint poses. Developed by Leap Motion, now Ultraleap

LPF **Low-pass Filter** 84

A type of filter that allows specific frequencies under a threshold value (cutoff frequency) through, but attenuates higher frequencies

MIC **Military-industrial Complex** 6

'Coalition of groups with vested psychological, moral, and material interests in the continuous development and maintenance of high levels of weaponry, in preservation of colonial markets and in military-strategic conceptions of internal affairs' (Pursell, 1972).

Earlier theses on the matter include Daniel Guerin's 1936 post-WWI analysis of the German and Italian fascist regimes: 'Starting from a desire to assure private enterprise maximum freedom, fascism is compelled to gradually bureaucratize the economy and is more and more trapped in the contradiction between what it would like to do and what it must do. Groping tortuously forward, it succeeds in maintaining the capitalist system, but only by restricting each individual capitalist's freedom of movement, and by sacrificing the other branches of the economy on the altar of heavy industry. Only the great capitalists continue to draw their profits, while the economy as a whole is paralysed and individuals of every class are ruined or put on short rations.' (1973, p.280)

MR **Mixed Reality** 3

Historically, a supercategory describing the spectrum of experiences afforded across the Reality-Virtuality continuum (Milgram and Kishino, 1994), although XR is now typically favoured. Recently, a term used by Microsoft, to distinguish their AR ventures from other companies.

MSAR **Multisensory Augmented Reality** 15

An AR system that offers real-time computationally mediated perception via stimuli across two or more sensory subsystems

MoMA **Museum of Modern Art** 27

A popular art museum in New York featuring contemporary works

MIDI **Musical Instrument Digital Interface** 65

Communication protocol often used in digital musical instruments. Typically, messages values between 0 and 127, are sent and received to change parameters.

NIME **New Interface For Musical Expression** 59

A research discipline, creative practice, and international conference that focues on applying human-computer interaction methods to the field of instrument and system design, evaluation, and performance

NFT **Non-fungible Token** 32

A form of digital property ownership characterised by its use of the public Blockchain ledger to prove authenticity of ownership of a unique digital item. The NFT itself is typically the proof-of-ownership, rather than the actual digital item, whose creator often maintains copyright. NFTs are typically purchased using a cryptocurrency

NGO **Non-governmental Organisation** 88

A type of organisation characterised by its independence from governments, typically non-profit

NS **Project North Star** 8

An open-source AR head-mounted display, released by Leap Motion (now Ultraleap) in 2018. see Project North Star Community

— **Open-source** 7

A term to describe a project or system whose ‘source’, i.e., the code from which a program is compiled, or design from which a device is built, is freely available to obtain and modify.

OSH **Open-source Hardware** 7

A philosophy that promotes the development and dissemination of hardware in an ‘open’ way that allows others to contribute freely to its design.

PDA **Personal Digital Assistant** 16

An early progenitor to the smartphone, that featured to many of the current capabilities found in them, e.g., a calendar, web browsing, information management, and a camera

PCB **Printed Circuit Board** 66

A type of solderable, copper-laminated board used to connect electric components

Pd **Pure Data** 58

A visual programming language developed by Miller Puckette in 1996 that is used for creating computer music systems

satnav **Satellite Navigation** 16

A technology that makes use of the Global Navigation Satellite System, a constellation of satellites (including but not limited to the U.S. 'GPS') that provides accurate positional data to satnav modules found in devices such as smartphones.

— **Sensor Fusion** . . . .

The use of algorithms to merge data from sensors to improve accuracy

6DoF **Six Degrees Of Freedom** 15

Six independent parameters available for change in a mechanical system. Often a short-hand term used to describe the tracked features of an inertial measurement unit (IMU) that can sense position and orientation in three dimensions, e.g., translation (movement) in x, y, and z; rotation in 'pitch', 'roll', and 'yaw'. This is often what enables XR headsets to track head and thus body pose

SHL **Sussex Humanities Lab** 102

A new-media reseach laboratory at the University of Sussex

VE **Virtual Environment** 12

A space characterised by its physical existence as digital bits

VR **Virtual Reality** 3

A technology, system, or process that facilitates real-time computationally simulated perception

XR **'X / All / Extended / * Reality'** 3

A supercategory describing any and all AR or VR experience, system, or process. The meaning of 'X' is topic of debate, with considerable pushback against the recent trend of it meaning 'extended'. Those opposed typically argue that the meaning of 'X' is rather as a wildcard or catch-all for 'any and all' (Mann et al., 2018).

Part I

HISTORY & PRACTICE

1 Towards Sound ARt Composition and Performance

Music, which should pulsate with life, needs new means of expression, and science alone can infuse it with youthful vigor.

(Varese, 1966)

1.1 Summary

In the last twenty years, computational technology has become more and more expressive, the systems we engage with becoming increasingly interactive. Due to this, the arts, including forms of digital sound art, have embraced new technologies in tandem with, and often contributing to, their development. This has led to more human-centred methods of designing tools of digital art creation, moving away from black-boxed (undisclosed to the audience) interactions, towards more performative and suggestive interactions, which often include the audience. Among some of the technologies that have seen nascent use in the arts is 'X / all / extended / * reality' (XR) [1], a group of technologies that promise to radically rethink the way we approach digital and physical reality.

The category of XR is comprised of: virtual reality (VR) - technology that promises to immerse us in a completely synthetic virtual world; and augmented reality (AR) - technology that promises to immerse us in our own real world through the computational mediation of virtual processes [2]. This leads to the augmentation, diminution, hybridisation, or extension of our own experience of reality, blurring and perhaps dissolving the line between our virtual and real selves.

AR, as mentioned, has seen sporadic use in the arts in the last twenty years. Its use in other disciplines, such as medical science, manufacturing and repair, annotation and visualisation, and the military (Azuma, 1997), have been typically characterised by its use as technology that aids or facilitates the **visual overlay and alignment** of **virtual graphics** (text, image, animation, video) onto our **real world environment**. Within these fields, this has a potential myriad important uses, from training junior doctors in dummy procedures by overlaying the steps of a difficult surgery, to allowing three-dimensional networked collaboration across vast distances. Within the arts, its use has also been typically limited to this 'visual overlay' approach. Despite being only a fraction of the possible forms of AR, this conception of AR dominates the market of consumer AR devices, from head-mounted, to handheld and projective technologies, the majority deal with overlaying visual information.

By taking a do it-yourself (DIY) approach to designing and implementing custom digital musical tools through hardware and software in Chapter 4, the present practice-based research thesis approaches AR through a multisensory lens to designing rich, expressive experience. The importance of such an approach is in its ability help redefine, and understand more about the

[1] The meaning of 'X' in XR is a hotly contested topic, check its term entry for more on its definition

[2] The present thesis makes no distinction between the modern usage of the term mixed reality (MR) and that of AR. Although commendable for being process-agnostic (i.e. mixed, not limited to augmentation), this thesis aligns itself with the larger body of academic research and creative practice that uses the term AR

technologies with which we are choosing to mediate our daily lives with, considering their origins, and also about how our own perception of digital media is affected through this embodied usage.

1.2 Personal Motivations

My own motivations for taking this approach AR experience is in the potential for it to afford creative, rich, sensory artwork, which seeks to teach us more about the way we perceive ourselves, others, and our environment. Coming from a background in music technology, specifically in developing and evaluating digital music tools and instruments, the nature of typical 'visual overlay' AR is seemingly incompatible with its use as a digital music tool. As such, it seems not only possible, but reasonable for it to be redefined to encapsulate all senses, and processes of perceptual modulation. In wanting to foster embodied experience between audience members (collaborative expression), AR offers a unique way of mediating and co-constructing the space in which they embody. Thus, my motivation is also within the advancement of our understanding this hybrid space-time, in which unique relationships between virtual and real processes are played out.

Real space, and increasingly virtual space, due to their pervasiveness and entanglement with the body, are inherently political media; substrates that we are all suspended in to different degrees, with their currents systemically shaped by those with political power or access to capital. They have and increasingly are being used to marginalise and commit violence against specific groups of people, through architecture, and through media. This thesis adopts my politics of being a green socialist, anti-racist, and feminist. Although it is by no means a political commentary, these positions are important to raise when outlining the rationale and motivation for the current work. As well as being a tool for violence and marginalisation, space, and specifically technologically mediated forms of space, can provide the foundation for radical acts of political expression through art.

Over the last three years, the NIME and sound art practice community has increasingly integrated XR into its toolset for digital musical instrument (DMI) design, evaluation, composition, and performance (e.g. Chevalier and Kiefer, 2017; Lee, 2020; Çamcı et al., 2021). Crucially, this comes at a time when corporations actively vie for a monopoly on virtual space, and by extension, our digitally mediated lives. Tangential to the questions outlined below, one of the main themes of the thesis is the accessibility, affordability, and sustainability of the digital tools used in sound art practice. This theme invariably involves the aforementioned anti-capitalist position, and thus aims where possible to reduce the amount of consumer technology used, in favour of DIY and Maker approaches.

1.3 Key Research Questions

As outlined, AR has seen nascent implementation as a creative medium in the arts, and more specifically music composition and performance. Therefore, the research areas and questions for the present thesis are based in the intersection between the arts, technology, sensory perception:

1. What is AR's genealogy, historical context, its contemporary forms, trends, exceptions, and definitions?
2. What theoretical underpinnings can we use to explicate AR experiences within an artistic context?
3. What are AR's boundaries and affordances as a medium, are there problems it poses artists and musicians?
4. What is the resultant experience for participants and audiences (or 'immersants') of an artistic AR experience?
5. What might a future corpus of artistic AR experiences and digital music instruments look, sound, and feel like?

1.4 Aims & Objectives of the Thesis

As well as answering and contributing understanding to the above research questions, this thesis aims to:

- Conduct a thorough literature and practice review of the field of AR generally and within the arts
- Apply theories of materiality, embodiment, and space to contemporary AR design, use, and evaluation.
- Contribute to the practice field of AR sound arts by designing and evaluating AR experiences for creative and collaborative expression.
- Contribute to the understanding of how such tools might affect our perceptions of self, others and our real, virtual, and hybrid environments.

- Propose workflows that may help artists and musicians interested in leveraging AR within sound art composition and performance

1.5 Research Methods

The research methods used to answer my research questions, and achieve my aims and objectives above involve taking a practice-based approach to designing multisensory digital musical instruments using AR. Much of this is grounded in a resistance to the origin of AR from within the U.S. military-industrial complex (MIC) ↺, and the effects this has had on the typical form of AR found today, explored in Section 2.6, and Chapter 4. In developing three sound augmented reality art (ARt) ↺ experiences, which were qualitatively evaluated through autobiographical design, and grounded theory coded interviews, I iteratively redesigned them to provide rich and immersive experience to myself as well as participants and audiences. This iteration has led to theoretical implications for the sonic medium found in Section 8.4, and a set of reproducible design patterns for artists and musicians interested in using AR creatively in Section 9.2.

1.6 Outline of Chapters

Chapter 2 starts with a review of AR as an emerging technology within the field of human-computer interaction (HCI) ↺, examining the effects that historical barriers to usage such as portability, price, as well as its origination in the MIC, have had on typical forms today. Among these forms, it is found that the majority deal with simple and descriptive visual additions in the form of text, image, animation or video overlay. I make a case for 'multisensory' AR, i.e. the designing of content or experience for multiple senses to counter not only this bias toward visual design, but also as a method of attaining richer and more novel experiences of AR. This case is made by examining current advancements in multisensory HCI applications and enabling technologies. In the second part of the chapter, I posit through a review of contemporary art practice, the potential of AR use within the arts in contributing to the designing and evaluation of expressive tools, enabling new aesthetic and multisensory experiences, collaborative expression, and agency.

In Chapter 3, I outline the position that the thesis takes regarding aesthetic experience and artistic production, as well as outlining a key contemporary theory of cognition: 4E cognition (4EC), that may help explicate aesthetic experience in AR. I identify three lenses through which to view, not only the potential of modern-day applications of sound ARt, but also the potential of the medium itself. The first is through a consideration of the **materiality** and form of complex processes in DMIs and interactive music systems for designers, performer, and audience. The second is through examining of current theories of enactivism and **embodied** action within XR technologies. The last is through considering the intervention of AR processes in real and virtual **spaces**, how this effects the construction of these spaces, the implications this in-turn has for the type of art that is created, and the privacy and security of people co-located in these spaces - is the Metaverse really where we want our ARt to exist and be ‘consumed’?

Chapter 4 contains the methodology through which I address my research questions, this is separated into three sections. First, I contextualise the methodological approach taken within the findings of the previous two chapters. Secondly, an outlining of the concept of resistance, which has guided and motivated my practical and theoretical work towards open-source technologies, non-visual sensory displays, and the processual nature of AR’s ability to modulate perception. Thirdly, I examine individually the methods taken in the ensuing three study chapters.

In Chapter 5, I outline the development and evaluation of the *area*~ system. *area*~ enables users to record, manipulate, and spatialise virtual audio samples or nodes around their immediate environment. Through a combination of ambisonics audio rendering and hand gesture tracking, this system calls attention to the ability of non-visual AR, here, audio augmented reality (AAR), to provide new aesthetic experiences of real and virtual environments. Through an autobiographical design (ABD) study, this pilot study proposes that rich experience can result from non-visual AR systems.

Chapter 6 describes the design, experience, and evaluation of an audiovisual (A/V) AR piece called polaris~, developed using mainly free / libre open-source software (F/LOSS) and open-source hardware (OSH). Studies took place in October 2021, and the experiences of 10 participants were analysed using the grounded theory analysis method to draw out commonalities. In evaluating *polaris*~ it was found that the experience engaged participants fruitfully, with many noting their ability to express themselves audiovisually in creative ways. The remarks from the transcriptions of these studies, that were then sorted into the categories of Sentiment, Learning, Adoption, Expression, and Immersion.

Chapter 7 outlines my journey deploying AR as a tool for sound ARt performance, detailing problems, solutions, and the experience of performing the piece *polygons*~ in AR. The performance was the first time I had immersed myself in the *polygons*~ system for an extended period of time which lead to an authentic exploration and improvisation of the material, embodied, and spatial affordances of the three instruments in the system *ambi*, *click*+-, and *hands*.

Chapter 8 briefly reviews the position of the thesis as carved out in Chapter 2 and Chapter 3, before discussing the DIY method outlined in Chapter 4. Combined results of the three studies are highlighted, and implications for the sonic medium of AR are proposed. Then, I propose a set of design patterns through which artists and musicians in the field can produce expressive works using AR. The thesis is concluded in Chapter 9 with a review of contributions, final thoughts, future recommendations.

1.7 Contributions

The contributions to knowledge of the present research cover four main areas, material, methodological, theoretical, and communal, and are as follows:

Material

The *area~* AAR compositional tool. Patch and schematics are available online.

The *polaris~* A/V AR experience. Code and patches are open-source.

The *polygons~* A/V AR performance system. Code and patches are open-source.

Design contributions to the accessibility of the Project North Star (NS) ⟳ headset.

Methodological

Presentation of *area~* at International Conference on Auditory Displays (ICAD) 2020 'Auditory Brown Bag at Home' series, and the Interact Conference 2021 'Multisensory Augmented Reality' workshop (evaluated in Bilbow, 2021*a*).

Presentation of research at Tangible, Embedded, and Embodied Interaction (TEI) 2021 'Graduate Student Consortium' (outlined in Bilbow, 2021*b*).

Presentation of *polaris~* at New Interfaces for Musical Expression (NIME) 2022 'Mixed & Augmented Reality' paper session (evaluated in Bilbow, 2022*a*)

Presentation on open-source AR for the CodeDay non-profit organisation.

Theoretical

Proposal of *'augmented materiality'*, *'augmented embodiment'*, and *'augmented space'* (Section 8.4).

Design Patterns for Sound ARt (Section 9.2).

Co-authored position paper on 4EC within sound ARt (Bilbow et al., 2021).

Communal

Performances and demos of *polygons~* (Bilbow, 2022*d*,*c*)

Peer-reviewed a paper on MR for Tangible, Embedded, and Embodied Interaction (TEI) conference.

Creation and maintenance of 'The XRt Space' website and Discord server.

Co-development and administration of the 'Arts Research Community' (ARC) Discord server at Sussex University.

Co-facilitation of the Embodiment Hackathon at Sussex University (Bonarjee et al., 2022).

Co-facilitation of the Leverhulme Sussex Seminar Series.

Co-facilitation of the Leverhulme Sensation Sussex Conference 2021.

2 Augmented Reality - Histories, Origins, Trends, and Problems

2.1 Summary

This review takes a retrospective view at the history of AR technologies. In laying clear the origination of these technologies within predominantly visual fields of research, it allows for a critique of preconceived notions about the definitions of what AR is, and the boundaries of how it is used today. The review outlines the contemporary forms, sensory display techniques, and methods taken to mediate our reality with virtual processes. In sketching out this wide variety of possible arising interactions, I make clear the benefit of considering AR as a medium for expressive computational artwork, namely in its inherent ability to approach technology from a creative and inclusive perspective (not just from the perspective of viewing AR as a visual overlay tool). I then touch on examples of AR art that make much more creative use of the materiality of AR in this way.

2.2 History of AR

The earliest conceptions of what we would today call AR began their development in 1965 with Ivan Sutherland's 'Ultimate Display' (1965). Sutherland's project, which was funded by the U.S. Defense Advanced Research Projects Agency (DARPA) ⥀, involved hypothesising and developing a computer interface that could serve 'as many senses as possible'. He speculated that this interface could 'serve as a looking-glass into the mathematical wonderland constructed in computer memory'. By 1968, Sutherland had constructed what he called a 'head-mounted three dimensional display', with a which was affixed to the ceiling of his lab with mechanical tracking arm that measured the position and orientation of the display in the room, called 'The Sword of Damocles' (see Figure 2.2).

Figure 2.2: 'Head-Mounted Three Dimensional Display' with 'The Sword of Damocles' ceiling mounted head tracking device (in Sutherland, 1968)

The head-mounted display provided per-eye visual displays via reflections from mini-cathode ray tube (CRT) ⥀ monitors, whose content was updated in real-time, dependent on the tracked pose of the head. This resulted in the three-dimensional (visual) perception of a hybridised real and virtual space.

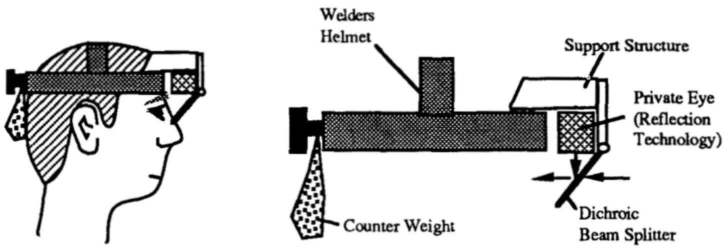


Figure 2.3: Diagram of a 'HUDset' using the PrivateEye (in Caudell and Mizell, 1992)

Over the course of the proceeding thirty years, most display (visual, audio and haptic) technologies gained higher resolutions, whilst becoming ever more miniaturised, propelled by the general movement towards ubiquitous and wearable computing. In 1992, AR was officially defined by Boeing engineers Thomas Caudell and David Mizell, as a technology that could be used to 'augment the visual field of the user with information' (1992). Their prototype device featured display and tracking technologies that built on the work of Sutherland. The purpose of Caudell and Mizell's device was to increase manufacture workers' efficiency through overlay of graphical wire-frame instructions. Their device operated by tracking elements of the users environment and body, processing these in real-time, and then overlaying these instructions via a PrivateEye [1] in the appropriate places dependent on the manufacturing process, through a heads-up display (HUD) called the 'HUDset'. The HUDset, commonly referred to today as a head-mounted display (HMD) operated by updating the display's output in real-time dependent on the position and orientation (pose) of the participant. This had the effect of the graphical overlay seeming 'fixed', or what is referred to now as 'registered' or 'aligned', on top of a specific point in the real world. For Caudell and Mizell, this display and tracking solution is what leads to the 'technology' of AR being possible, and for them, it is what enables the context-aware instructional overlay of their application.

Shortly after this original definition, Milgram and Kishino conceptualised the 'Reality-Virtuality Continuum (1994), which aimed to consolidate similar efforts across disciplines that were aiming to augment or virtualise 'reality'. The continuum (see Figure 2.4) defines two outer bounds of 'Real Environment' on the left (which exist as physical and tangible matter), and 'Virtual Environment' on the right (that exist solely as digital bits), and everything within was to be classed as mixed reality (MR). Within MR, use-cases closer to the 'Real' were regarded as AR, and use-cases closer to the 'Virtual', were regarded as 'Augmented Virtuality' (AV). In separating these MR use-cases from the tele-robotics field of VR and virtual environments (VEs)

[1] https://billbuxton.com/Private_Eye_Brochure.pdf

⥀, they proposed a clear framework for classifying works. Since both AR and AV make use of augmenting 'by means of real objects' in today's use cases, (e.g. by tracking and parametrising hand gestures, or tracking and generating spatial maps of the real environment), the difference between AR and AV in this definition, problematically, becomes the 'primary world' in which objects are are doing the augmenting. Indeed, Milgram and Kishino make note of the possibility of this in their paper:

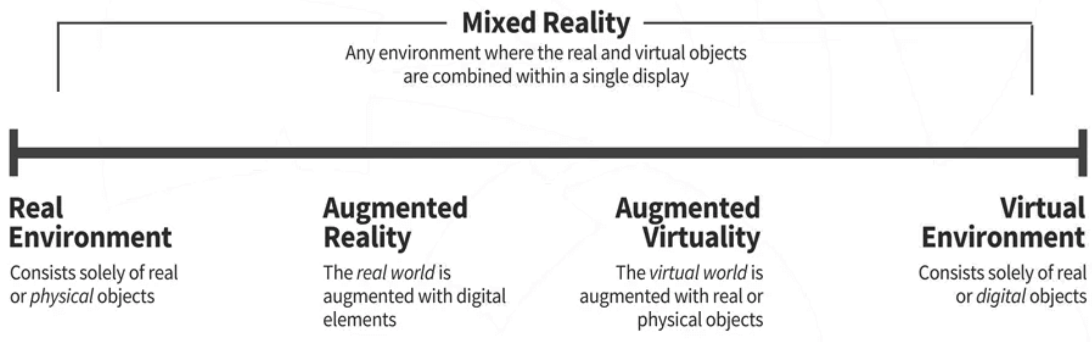


Figure 2.4: Adaptation of the 'Reality - Virtuality Continuum' by Milgram and Kishino (in Tremosa, 2022)

'Of course, as technology progresses, it may eventually become less straightforward to perceive whether the primary world being experienced is in fact predominantly 'real' or predominantly 'virtual', which may ultimately weaken the case for use of both AR and AV terms'

They further specify that, despite this is the case, it should not affect the validity of the more general MR term to cover the 'grey area' in the centre of the virtuality continuum, and also offer the term 'Hybrid Reality' for displays that blend AR and AV compositely. Today, the term MR is seen seldom apart from its use within Microsoft's 'Mixed Reality Toolkit', and 'Hybrid Reality' even less so. Therefore, as previously mentioned, due to the rapid evolution of these technologies, the present thesis makes no distinction between Mixed, Hybrid, and Augmented Reality.

In 1997, Azuma et al. proposed a specification for the definition of an AR system, and surveyed the five years of AR research since Caudell and Mizell's original definition. In order to avoid limiting AR to specific technologies, they define AR as a 'system' that follows three characteristics:

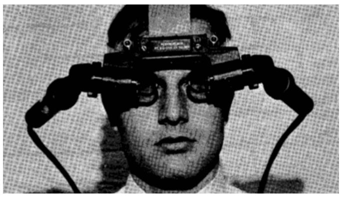
- Combines real and virtual
- Interactive in real time
- Registered in 3-D

In this project, also funded by DARPA, Azuma distinguishes between optical and video based approaches to AR. While both of these methods had been realised via visual HMD technologies, Azuma makes further room in the definition for monitor based approaches too, allowing the definition to be broad enough to encompass a variety of AR use cases, methods and processes. Not soon after, Azuma et al., classify three categories of 'display': head worn, handheld and projective. For this reason, as well as the specification of three precise characteristics, Azuma's definition of AR has become widespread.

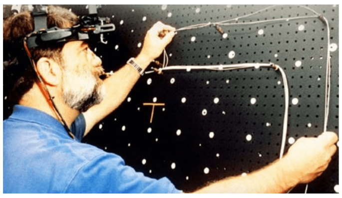
2.2.1 Exceptions to the Rule

These early definitions and conceptions of AR were typically built upon with applications involving display and tracking technology that resulted in the **visual overlay and alignment** of **virtual graphics** onto our **real world environment**. Whilst this view of AR is followed by the overwhelming majority of historical and contemporary AR applications, it only makes up a small subset of the potential myriad interactions afforded by the technologies that enable AR. Sutherland, who arguably catalysed early practical research in this field, viewed this AR as a 'window' interface, that could serve 'as many senses as possible'. Louis Rosenberg, a researcher at the U.S. Air Force Research Lab, another early proponent of AR, developed the concept of 'Virtual Fixtures' (overlaid sensory information) as a method of reducing the 'tax' on our senses induced by an overload of information through the visual sense (Rosenberg, 1993). Milgram and Kishino, in outlining their taxonomy, recognise that it could serve to alleviate 'analogous issues associated with other display modalities', and cite work from Cohen, who at the time was developing realistic acoustic environment rendering in AR (1993). They also note the concurrent work in haptic (the various senses of touch) displays for AR.

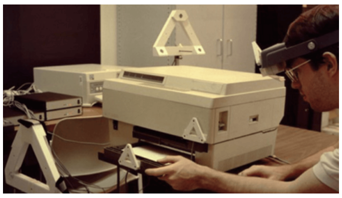
At odds with the typical overlay approach, wearable computing pioneer Steve Mann coined 'Mediated Reality' (1994) as descriptor of a methods used to computationally mediate our own perception, rather than focusing on the overlaying paradigm. His later work terms 'All Reality (*R)' which broadens the taxonomy of AR with concepts such as as surveillance and privacy (2018). Azuma et al., also acknowledge that AR is not just limited to visual perception or overlaying processes: 'AR can potentially apply to all senses, including hearing, touch, and smell. Certain AR applications also require removing real objects from the perceived environment, in addition to adding virtual objects'. With this in mind, what does the landscape of more contemporary AR design look and feel like today?



(a) ‘Head-Mounted Three Dimensional Display’ (in Sutherland, 1968)



(b) ‘HUDset’ (in Caudell and Mizell, 1992)



(c) ‘KARMA System’ (in Feiner et al., 1993*a*)

Figure 2.5: Augmented Reality Head Mounted Displays in the 20th Century

2.3 Forms of AR

2.3.1 Head-mounted

Successors of AR HMDs devised by Sutherland (1968), Caudell and Mizell (1992), and Feiner (1993*a*; 1997) exist today commercially within products such as the Microsoft Hololens 2 [2], the Magic Leap ML-1 [3], and the nReal Light [4]. These devices afford optical see-through capabilities through half-mirror visors and high-resolution displays, and offer stereo audio output. Input is managed mainly by hand-tracked interaction with overlaid visual menus and objects, but is also possible through eye tracking and voice control. The environment is sensed through a combination of six degrees of freedom (6DoF) tracking, and spatial mesh mapping. For most HMDs today, this input and environment processing occurs off-device, on a tethered or wearable computer, or mobile device. These devices tend to be relatively expensive due to the extremely high R&D costs associated with the field (due to its novelty). Leap Motion’s open-source NS [5] headset provides a much cheaper alternative at the trade-off of slightly larger form and lack of integrated computing and audio implementation, but has the highest field-of-view of all four and comparable tracking.

A device that is head-mounted poses clear benefits to both input and output modalities. For input sensors, being mounted on the head provides them with more accurate tracking from the perspectives of our own senses. Consequently, and as Lindeman and Noma maintain in their classification scheme for multisensory augmented reality (MSAR), an important factor for the parity (if desired) of real and virtual output, is a consideration of the location along the ‘stimulus pathway’ at which they mix: at the environment, sensory subsystem or computer level (2007). For a device to be head-mounted, allows ‘mixing’ to happen closer to the sensory subsystems, e.g., our eyes, ears, nose and mouth, thus resulting in an experience that is more

[2] https://www.microsoft.com/en-us/hololens
[3] https://www.magicleap.com/magic-leap-1
[4] https://nreal.ai/product/
[5] https://docs.projectnorthstar.org/

(a) Microsoft Hololens 2 (from Microsoft, 2022)

(b) Magic Leap ML-1 (from AT&T, 2019)

(c) nReal Light (from nReal, 2020)

(d) Leap Motion Project North Star (in Bilbow, 2022*a*)

Figure 2.6: Augmented Reality Head Mounted Displays in the 21st Century

closely intertwined with our real-time environment stimuli.

2.3.2 Handheld

Today, anyone who owns a smartphone is carrying an AR device in their pocket. This particular genre of AR development began in earnest in the mid 2000's and today is the most widely used form of AR due to the pervasiveness of smartphones. It builds on the early research and practice of handheld AR applications built on cellphones and personal digital assistants (PDAs) in the late 1990's, and smartphones in the late 2000's, whose increasing variety and accuracy of onboard sensors: cameras, gyroscopes, accelerometers, and satellite navigation (satnav), provided a convenient all-in-one solutions for developing handheld visual AR experiences.

The limitations of handheld displays are outlined by Bimber and Raskar (2005, pp. 79-83): reduced immersiveness due to the small screen size, compounded by the distance between it and the participant (normally arms length), impaired gestural input due to the need to hold the device; restrictions due to the cameras image quality and less computational power available to effectively register (align) real and virtual objects. As well as these issues, smartphones have developed to be primarily visual devices despite their name, and as such, their ability to deliver high fidelity audio, let alone AAR mixing is limited due to their distance from the ear.

Recently, the lack of non-visual AR in handheld smartphones has been addressed through the increased adoption of ‘hearables’, a marketing term for small and unobtrusive, wireless earphones. More specifically, two features make these suitable audio solutions for AR use; ‘transparent’ hearing modes (see mic-through (Lindeman et al., 2008)), and integrated 6DoF tracking [6].

2.3.3 Projective

Projection of data into the environment in order to overlay or alter perception of real objects, i.e. mixing virtual and real stimuli at the environment level (Lindeman and Noma, 2007), is perhaps the least adopted of Azuma’s categories of AR. The property that sets projective AR apart from head-mounted and handheld AR is its potential to deliver experience to multiple participants within a shared space. Although collaboration is possible through the previous two categories, it requires all participants to engage technology that is affixed to their body (either through wearing or through holding). Projective AR alleviates both the burden of physical attachment to a device, and also the expense of procuring a device for each participant. This category of display is typically realised by use of video projectors and speaker arrays. Although the base requirement of registration in three-dimensions between virtual and real (Azuma’s third specification), is fulfilled relatively easily compared to head-worn and handheld approaches (more sensor computation and accuracy),

2.3.4 Other Forms

Of course, this categorisation of forms is not exhaustive, and leaves out body worn AR systems such as haptic vests, systems that take on more than one form such as the Audiomented Sound System / Parabolic Mirror in Listening Mirrors (Chevalier and Kiefer, 2020), and sonically tangible virtual objects (Schraffenberger and van der Heide, 2015). I will expand on these cases in Section 9.2.2, where I lay out a design pattern for considering wearable, tangible, and situated AR instruments.

2.4 Sensory Display in AR

Within these common forms of AR technology, one could split the various technological processes that occur into input, process, output (the general IPO model found in software engineering), in AR this is often labelled: tracking, process, display. Tracking, as mentioned is often through hand gesture, body position and orientation and voice activation. Display is managed

[6] https://www.apple.com/airpods-pro/specs/

in the majority of cases through screens. The present section outlines various other sensory displays that have the potential of creating more immersive tools of expression.

2.4.1 Visual Sense

It is poignant to mention that until that last 20 years or so, sensory sciences, and as a result, technological displays of information, were focused on the visual, with the auditory following behind, and then the touch, smell and taste senses. In cross-modality psychology research, this ocularcentrism (the perceptual and epistemological bias ranking vision over other senses) is normally explained by a 'textbook' explanation: 'the idea that vision is the most important modality is supported by numerous studies demonstrating visual dominance.' Fabian Hutmacher argues that ocularcentrism can be critiqued through the lenses of (2019):

- A methodological-structural explanation: 'Research on vision is often easier than research on other modalities and that this is the result of an initial bias toward vision that reinforces itself.'
- A cultural explanation: 'The dominance of the visual is not a historical constant, but rather a result of the way (Western) societies are designed.'

However, AR is still typically realised in the form of graphical overlay, and as such, the forms which we find ourselves interacting with are predominantly based around screens and other forms of visual display (Dey et al., 2018). These are often split into optical and video see-through methods of display. The former employs semi-reflective half-mirrors to combine the reflection of close-by screen with the natural pass-through of the real world; the latter uses the feed of cameras to completely occlude the participant's vision, and performs AR processes on top of the camera feed. There are advantages and disadvantages to both methods, outlined in (Rolland and Fuchs, 2000). Head-mounted systems tend towards optical see-through, whereas most handheld AR (smartphones) are exhibit video see-through AR.

2.4.2 Auditory Sense

The second most developed-for sense in AR is the auditory system, borrowing from a rich history of spatial audio techniques such as exploiting head-related transfer functions (HRTFs) for binaural audio playback and realistic audio localisation (Blauert, 1969, 1996). Within the field of AAR, as previously mentioned, 'hearables' with 'transparency hearing' modes offer the auditory equivalent of video see-through (coined mic-through (Lindeman et al., 2008)), where the occluded outside world is captured through a microphone, on top of which virtual sounds can be processed. Also outlined by Lindeman and Noma is the use of bone conduction headphones to offer a mediated perception of sound environments without the need to occlude the participants ears (coined hear-through), which could be considered equivalent to optical see-through. Moving into the environment, there are a myriad spatial audio techniques that could be used within AR, delivered by speaker arrays such as those found in wave-field synthesis (Berkhout et al., 1993) and ambisonic beam-forming practices (Sharma, 2018; McArthur, 2019).

2.4.3 Haptic Sense

Due to the prevalence of hand-tracking technologies in the interaction with head-mounted AR applications, one might assume that being able to actually *feel* the virtual objects that are placed in AR would be one of the most important and developed concepts in AR. However, much of the early research in AR placed importance around overlaying instructions, rather than interactive objects. Hence, the haptic feedback of touching AR objects is relatively under-explored compared to the common issues which affected early and (funded) research - accurate registration of real and virtual processes; and higher visual fidelity. In most cases, it was deemed enough to *see* the effect that ones hands or body position had on the AR object or scene respectively. Today, there exist numerous technologies that could provide computationally mediated haptic perception in AR, for example through vibrotactile feedback or electrical muscle stimulation (Lopes et al., 2018), and more recently ultrasound mid-air haptic sensations Ablart et al. (2019).

2.4.4 The Chemical Senses

Whereas auditory and haptic sensations have been developed in AR, the chemical senses (smell and taste) have received far less exploration. Visual, auditory, and touch information can be believably recreated with technology through analog to digital conversion of electromagnetic radiation (light) and mechanical wave transmission (sound and touch). Conversely, smells and tastes contain organic information, the sensors (and thus analog-digital conversion) for which have not been invented yet. As such, the closest we can get to receiving chemical sensory data is through computationally activated rather than computationally medi-

Figure 2.7: A participant shown in (a) VR and (b) artificial composite mixed reality. The participant is being warmed by a furnace, as the device atomizes a cayenne pepper tincture (capsaicin) to create a warming sensation in their nose (in Brooks et al., 2020)

ated displays: scent emitters (Maggioni et al., 2019), and taste patches for example. Accordingly, in order to mediate the sense of taste, creative methods of sensory illusion have often been employed, e.g. Narumi et al. demonstrating that the sense of flavour can be mediated via visual overlay in AR (Narumi et al., 2011). The sense of temperature has also been mediated through cross-modal sensory illusion (see Figure 2.7) exploiting the trigeminal nerve in the nose, Brooks et al. demonstrate that users in VR can be made to feel warmer or colder based on the relative amounts of capsaicin or eucalyptus emitted near the nose (2020).

2.5 Processes in AR

Additive layering of virtual content onto our real environment is by far the most typical of processes experienced in AR. However, it is only one of the potential methods of interaction between virtual and real components. In navigating this issue, the present thesis aligns its conception of AR closely with the definition of AR by Chevalier and Kiefer (2020): 'real-time computationally mediated perception', which fulfils Azuma's three characteristics of AR systems, but is not as exclusionary as Caudell and Mizell's original definition: a technology used to 'augment the visual field of the user with information'. Investigating the existing relationships between real and virtual components of AR systems, Schraffenberger outlines at least five 'relationships' and five 'subforms' of AR (see Table 2.1). This taxonomy (2018, pp. 80-130) provides an ideal starting point for those designing AR systems interested in creating embodied experiences that challenge the typicality of basic visual-overlay AR. Furthermore, Mann expands the 'Reality - Virtuality Continuum' (Milgram and Kishino, 1994) into the 'All Reality Continuum', integrating further dimensions such as 'Metaveillance', 'Kineveillance' and 'Phenomenality', such a standpoint not only 'anticipates the need for an ethically aligned reality' (2018), but demonstrates the multifaceted nature of AR to afford experiences of ourselves, others, and environments computationally mediated by more than just additive informational overlays.

In particular, 'diminished reality', aims to *remove* real objects in our environment. When explored in the visual sense, this approach uses computer vision and content-aware substitution to remove a section or object of the real-world environment through camera sensors. Noise cancelling potentially offers an auditory diminished reality, but due to the fact that sound is propagated via mechanical waves, our sense of sound is closely intertwined with physically feelings of vibration, which are much harder to remove (Mori et al., 2017). Further examples of sound-driven but cross-modal techniques are outlined in (Walther-Hansen and Grimshaw-Aagaard, 2020).

Relationship	Description
Coexistence	Unrelated
Presence	Spatially Related
Information	Content-Based Relationship
Physical	Affect Each Other
Behavioural	Sense and React to Each Other
Subform	**Description**
Extended Reality	The Virtual Supplements the Real
Diminished Reality	The Virtual Removes the Real
Altered Reality	The Virtual Transforms the Real
Hybrid Reality	The Virtual Completes the Real
Extended Perception	Translating the Imperceptible

Table 2.1: Taxonomy of relationships and emergent AR subforms (in Schraffenberger, 2018)

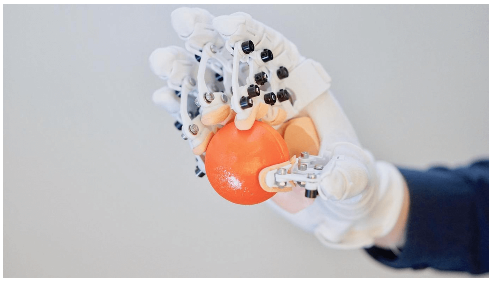


Figure 2.8: 'HandMorph' offers altered touch perception by reducing hand affordances (in Nishida et al., 2020)

'Altered reality' has the potential to provide new and otherwise inaccessible sensory and perceptual experience Schraffenberger describes that this is possible through virtual components altering the perception of real components in an AR system. Mann outlines a myriad examples of altered visual percepts (1994), from giants eyes, to 'slow' glasses. More recently, Nishida et al. have experimented with 'egocentric smaller-person experience' through use of a video see-through AR headset, in which unlike typical AR, the cameras are mounted at waist height, rather than on the HMD (2019). This afforded participants a difference in real-time visual perception, and resulted in them generally feeling smaller and behaving more like a child. In tandem with this altered visual perception, they propose a modified robotic glove 'HandMorph' (2020) that alters sensations of touch through reduced finger and overall grip size.

In a similar vein, 'extended perception' revolves around the potential to provide *more* senses, or the sensing of stimuli outside of the range of our sensory systems. Bees for example have a visual system that extends far further into the ultraviolet range of EM radiation than our own eyes allow us; dogs hear much higher frequencies our ears allow us (thank goodness); and sharks can smell one part blood in a million parts water. These fun facts demonstrate vast differences in sensory acuity between species; but did you know that some shark have a constellation of pores [7] along the lateral side of their bodies that allows them to perceive minute pressure changes in water? This enables them to create a 'pressure map' of their surroundings through active body movement. Modern technology could endow us with similar and myriad extended perceptions of our environment and its stimuli; Mann has experimented with making representations of radio waves translated down to the sensory range of our own eyes (2018).

This section demonstrates the multitude of potential experiences that AR affords beyond mere visual information layering, next, I will examine the usage of AR in the arts, as a medium or tool for creating immersive aesthetic experiences, and demonstrate how this contributes towards a more holistic understanding of AR as a technology.

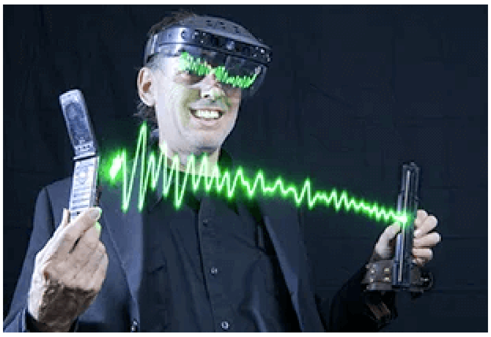


Figure 2.9: 'Sequential Wave Imprinting Machine' allows visualisation of radio waves in AR (in Mann, 2018)

2.6 AR in the Arts

The present chapter has outlined the origins of AR technology in funding from the U.S. MIC. This is in the hope of making clear that the challenge faced by AR's co-option in experimental and progressive art is not just one that is at odds with its origin technologically and functionally, but also ethically, morally, and socio-culturally. The dominance of the visual sense, and of the process of overlaying, is a direct consequence of the importance of these approaches in the military and industry applications of AR (and more generally, digital technology) within the the capitalistic and colonial pursuits of Western 'foreign policy'. Pursell writes that the MIC has a vested interest in the 'maintenance of high levels of weaponry, in preservation of colonial markets, and in military-strategic conceptions of internal affairs' (1972). Let us not forget that the first explicitly defined 'AR' application was as a tool to increase worker efficiency (Caudell and Mizell, 1992), perhaps for safety, perhaps for quality assurance, but most likely for streamlining the workforce and increasing profits. Around the same time, HUD technology was being used by the military to increase the deadliness of U.S. fighter pilots by offering the tactical advantage of visual and auditory overlay of target locations (Wanstall, 1989).

One might be mistaken for thinking that this was just an opening chapter in the story of AR, but for those of us who oppose the regressive neo-colonial and capitalist elements of global

[7] https://www.sharktrust.org/shark-senses

MICs, AR technology is still very much in receipt of advancement from these same industries. In 2018 the U.S. Army was looking to award a contract worth over $500 million USD to an AR headset manufacturer for the production of 100,000 headsets for their soldiers to 'increase lethality by enhancing the ability to detect, decide and engage before the enemy' (Brustein, 2018). Both Magic Leap and Microsoft bid on the contract, with Microsoft ultimately being awarded it. The outlined example may read as being a consequence of 'technological progress', but I hope to impart that this is the intended direction of AR funding, rather than an accident. Of course, this is not a new story. This tortuous but symbiotic relationship between avant-garde art practice and institutional laboratories funding by the MIC is explored in 'Technocrats of the Imagination'.

> The art-and-technology projects of the 1960s mark the meeting point of the post-formalist experimentalists of an ascendant American art and the federally funded military-industrial university R&D machinery of the Cold War superpower. What these very different constituencies share is a commitment to continuous innovation in the design and application of technology, an understanding that this process requires collaborative experimentation, and that such a process is, broadly speaking, a social good, whether that means enhanced national security and an improved standard of living, or new modes of experience and understanding. (Beck and Bishop, 2020)

How, as artists and musicians opposed to the pursuit for what can only be described as techno-dystopian Microsoft 'super soldiers', can we navigate this space morally and co-opt these tools for positive social change – is it even possible? Moving forwards I would like to suggest three areas from which we may be able to think about AR differently. These stem from the categorisation of AR by Azuma (1997) but aim to go beyond the technological and functional, which may be tinged with values and predispositions towards military and industrial applications. This is in order to engage with these three characteristics from a digital arts and humanities perspective, considering the lenses of materiality, embodiment, and space:

Azuma et al. specify:

- AR combines real and virtual
- AR is interactive in real time
- AR is registered in 3-D

We ask:

- How does this combination result in **material** that makes up an AR experience?
- How do interactive AR experiences engage our sense of **embodiment**?
- How can we describe the hybridity of registered **space** in AR experiences?

Agreeing that AR can be used as a medium for the composition of computational art, provides the starting point from which to answer these questions. As Papagiannis highlights, we ought to develop an understanding of the 'capacities of the technology and its constraints, to exploit the technology to artistic use by envisioning novel applications and approaches, and developing new aesthetics and conventions beyond previous traditional forms' (2017). If visual overlay AR has been used as 'a viewing instrument to bring into focus forces invisible to the naked or unknowing eye, and make them visible in the public sphere.' (Thiel et al., 2011), what emergent properties might applications rising out from multisensory approaches to design afford? What are the futures of digital musical instruments, whose designers opt to use this medium?

Among other creative fields, computational art has already seen some nascent implementation of AR as a medium. Computational art, the use of computational programming or software as a tool, performance aid, medium or collaborator to create art or artistic works, is currently witnessing the adoption of new and exciting technologies such as trained machine learning algorithms, increasingly immersive displays and large-scale networked experiences. These implementations of technology within the creation of artworks leads to a greater understanding of the materiality of these technologies, and perhaps greater understanding of the self and others. In this section, I draw attention to contemporary examples of artworks that demonstrate the modes of sensory engagement, aesthetic experience, collaborative expression, and activism that AR specifically affords these artists that are willing to exploit its use as a medium.

2.6.1 Sensory Engagement

Computational art has seen the use of AR as a medium since the mid 1970s's, in pioneering media art that used retro-reflective glass illusions such as Jeffrey Shaw's 'Viewpoint', and 'Virtual Sculpture' (1975; 1981). After the advancements in computing and display technologies of the late 1990's and early 2000'sIn 2008, Grasset et al. presented case studies of AR art exhibitions, with the conclusion that for effective design of artworks, specific importance should be placed on the relationship *between* real and virtual components (2007). These relationships have come to describe a matrix of possibilities between senses and mediating processes, e.g. altered hearing, extended smell, diminished sight. Papagiannis has drawn attention to this broader multisensory view of AR in attempting to understand an aesthetic for AR applications, 'AR is beginning to expand in new ways, beyond visual frames and into the full human sensorium' (2014). In 2015, the Tate Sensorium multisensory art exhibition used novel mid-air haptic devices to augment visual art (Vi et al., 2017). The results of the included study found that more congruent multisensory experiences lead to audiences finding artwork more emotionally engaging. If more congruent multisensory experiences of art lead to more emotional engagement, and AR has the potential to mediate multiple senses in rich and provocative ways, surely this makes it an ideal medium for such works.

Figure 2.10: Tate Sensorium multisensory ARt providing audio and haptic augmentation (in Vi et al., 2017)

2.6.2 Aesthetic Experience

Chevalier and Kiefer highlight the nascent use of newer AR technologies by artists (2020). They argue that AR has far more potential for creative exploration, and that it is a medium for creating 'new nuanced and fine-grained emergent aesthetic experiences' and as previously mentioned, necessarily define AR as 'real-time computationally mediated perception' in order to be inclusive of a multisensory approach to design.

The installation 'Concrete Storm'[8] by artists Gordijn and Nauta demonstrates the ability for AR to afford novel experiences of seemingly immutable and rigid physical objects (short concrete pillars), through the extension and animation of the concrete into larger, shifting and breaking structures. In describing the design of the work, they outline one of the main impetuses

[8] https://www.studiodrift.com/concrete-storm-microsoft

of creating the work: 'Gordijn says the duo was interested in beginning to investigate the point at which viewers 'might let go of trying to distinguish between what is real, what is not' and accept this new mixed world as simply another version of reality' (Gottschalk, 2017).

Figure 2.11: Composite AR view of Concrete Storm (from Gordijn and Nauta, 2017)

2.6.3 Collaborative Expression

Another key aspect of the use of AR as a medium in computational artworks is its ability to enable collaborative expression and construct shared perceptual spaces. For example, Listening Mirrors[9], an artwork by Chevalier and Kiefer, (2018) is an AR installation that engenders a collaborative and performative AR sound environment. This environment is hybrid in nature; split between physical and virtual space. In the installation space, participants can interact with a audio augmented parabolic acoustic mirror. Their interactions are intertwined with a computationally mediated virtual sonic environment that they experience through bone conduction headphones. Additionally their vocalisations are mediated by a wearable microphone through the mirror. This invites collaborative expression through exploration of the shared sonic world.

Similarly, Eno and Chilvers explore collaborative ambient A/V composition in their AR adaptation of the popular app 'Bloom', 'Bloom: Space' (Eno and Chilvers, 2018). In this installation, participants wear a Microsoft Hololens and use hand gestures to activate and manipulate generative A/V elements. These elements can be experienced by other participants and thus create a shared perceptual and actionable space.

[9] http://listeningmirrors.net/

(a) A participant interacting with the acoustic parabolic mirror in Listening Mirrors (from Chevalier and Kiefer, 2019)

(b) Three immersed participants, creating sonic ARt in the Bloom: Space experience (from Ray, 2018)

Figure 2.12: Collaborative Expression in AR

2.6.4 Activism and Agency

Due to its ability to be an effective tool for collaborative expression, or perhaps because it creates a liminal hybridity that 'questions the possession and control of a physical space' (Thiel, 2018), AR art has seen use in activism and collaborative political expression. Early pioneers such as the Manifest.AR group were able to create convincing and socially immersive AR art using visual layering (Veenhof and Skwarek, 2010). They did this through aligning the collaborative potential of AR with political expression. By creating an app that overlaid visual art within the Museum of Modern Art (MoMA) through satnav, they allowed participants to visit an exhibition in the museum that had not been organised by MoMA themselves (Figure 2.13(a)). AR thereby afforded these artists the ability to embed virtual art within an area considered private property, and also promote collective AR agency, raising very early questions about 'virtual trespass' with AR. In a similar vein, '#arOCCUPYWALLSTREET' (#arOWS) was an arm of the Occupy Wall Street protests of 2011. Some 25 artists succeeded in overlaying the Wall Street area with 'over 400 protest related augments', including audio overlays of protesters who were forbidden by police to enter the area. In this way, 'AR was able to overcome their surveillance, barricades, horses, and excessive police numbers' (2018) and more easily provide the means to action to people unable to physically mobilise.

As well as its liminality between real and virtual space promoting otherwise dangerous collaborative expression, AR has the power of rendering the invisible as seen, and due to this, it is a tool that has be used to shine light on social, economic, political and environmental injustices. Through its ability to change our perception of the real world through sensory augmentation, diminishment, hybridisation and extension, it has been used as a medium within the arts to 'uncover' underlying mechanisms in our society. For example, Thiel and PATTU's (artists Cem Kozar and Işıl Ünal) 2011 work 'Invisible Istanbul' aims to render the unseen urban dynamics of Istanbul visible through smartphone visual overlay and satnav. They write: 'Viewers become as

(a) Manifest.AR MoMA Invasion (from Veenhof and Skwarek, 2010)

(b) Invisible Istanbul (from Thiel et al., 2011)

Figure 2.13: Activism through Interventionist ARt

photographers: the act of viewing or making a screenshot of the objects at a specific site and time reifies the virtual objects into artworks, revealing hidden forces within the city not visible to the naked eye.' (2011). In PATTU's work, an AR walking tour, different parts of the city are overlaid with symbolic information of past, present, and future uses of each area, highlighting tensions from military and commercial uses, and the effects this has on 'contemporary urban space and the lives of its inhabitants' (2018).

As summarised by Manifest.AR member Martin Skwarek: 'Alice has stepped through the looking glass [...] It is the job all future artists and activists to use this technology for the better, to bring people together, and uproot social injustice.' (2018)

The next chapter delves into related research areas, including from the field of interactive music systems, where this thesis is situated, to further understand the *materiality* afforded by AR when used as a medium for creative expression specifically within sound art and music, the experience of *embodiment* it has the potential of imparting on its immersants, and the hybrid real-virtual *space* it co-constructs with them when in use.

3 Aesthetic Experience, Complex Music Systems, and the Metaverse

In actual experience, there is never any such isolated singular object or event; an object or event is always a special part, phase, or aspect, of an environing experienced world—a situation'

(Dewey, 1934, p. 67)

3.1 Summary

In the previous chapter, I outlined the problematic origins of AR technology from within the U.S. MIC. This origination from within neo-colonial and capitalist modes of thought has had a compounded effect on the form that AR takes today: predominantly it is sought as a 'visual overlay' device. Despite this, clearly limiting perspective, we are seeing (or indeed hearing) increased use of AR as a medium for the creation of meaningful experiences through interactive artwork. Though fairly established in modes of visual art because of this predominant form, its use in sound related art forms has been limited. As a result, the present thesis promotes a sensory-process agnostic [1] conceptualisation of AR, by using the more holistic definition 'real-time computationally mediated perception' (Kiefer and Chevalier, 2018) moving forwards.

But first, we must carve out a space for the consideration of AR as a medium for new forms of aesthetic experience in specifically sound-driven art forms, such as composition, performance, installation, and instrument building. This chapter does so by first outlining what we mean by aesthetic experience. In delving deeper into contemporary theories of embodiment, I propose (as others have done), that an enactivist approach to design guided by the 4E's (embodied, embedded, enactive, extended) may be beneficial when considering the *material*, *embodied*, and *spatial* nature of interactive music systems, and more specifically, those that employ AR. From this foothold, the chapter goes on to considers a trio of theoretical lenses through which to consider the process of mediation in AR experience, and the types of aesthetic experience this results in. Namely, by exploring the concept of complexity in the **materiality** of interactive musical systems; enactivist approaches to considering **embodiment** in XR systems; and a brief discussion on why the Metaverse (at least in its current form) is not the ideal **space** for artistic expression.

3.2 Knowledge and Aesthetic Experience

What is experience when it comes to art; how does it relate to epistemological practice? To address this question, the present thesis draws from the work of the American pragmatist John Dewey (1859-1952). In his 1934 text, Art as Experience, Dewey argues that the production and consumption of art faces a crisis. After having been historically coupled in an constitutive relationship with the processes of everyday sociocultural life, it is being increasingly separated from these 'conditions of origin and operation in experience' (Dewey, 1934), in a way that places art upon a remote pedestal. Dewey describes this as a product of the growth of capitalism. On

[1] That is to say, not limited to visual sensory displays, and not limited to augmentation processes

proposing what they term Dewey Aesthetics, Leddy and Puolakka write:

> 'Nothing about machine production per se makes worker satisfaction impossible. It is private control of forces of production for private gain that impoverishes our lives. When art is merely the 'beauty parlor of civilization,' both art and civilization are insecure. We can only organize the proletariat into the social system via a revolution that affects the imagination and emotions of [hu]man[kind]. Art is not secure until the proletariat are free in their productive activity and until they can enjoy the fruits of their labor. To do this, the material of art should be drawn from all sources, and art should be accessible to all.' (2021)

From this standpoint, art can serve as an emancipatory force for positive social change; but only on the condition that it is first brought back to the 'origin and operation' of everyday experience — through the democratisation of a wider corpus of artistic media, tools, and social contexts in which these are deployed. In the 21st century, we could mistake this for already having happened. The increasing availability of ubiquitous technologies such as the internet, wearables, smartphones, powerful computers and software have shifted artistic production closer to the site of everyday sociocultural life — i.e. from the studio to the bedroom. Yet in doing so, has art really been knocked from its pedestal and been re-integrated into, and resituated to arise from everyday life?

Today, the fabric through which art tends to be disseminated and therefore consumed, centralised social media platforms, arguably operates within this same profit motive, the vocabulary having shifted from 'art in the museum', to 'content on our feeds'. Indeed, Despite making art more accessible to produce and consume, the capitalist logic of surplus extraction the centre of the algorithms that determine our interaction with centralised social media platforms vies to keeps art separate from everyday life.

They are not solely focused on fostering individual or even collective curation of democratised art/content. They still employ the capitalist framework at their core. In other words, the extractivist profit motive defines the algorithmic fabric of online 'content creation' (production), and resultant social media 'engagement' (consumption) through mass data harvesting and advertisement selling. The longer users are engaged on a platform (Facebook, Instagram, Twitter, YouTube, TikTok), the more likely they are to generate profits for the platform via advert click/tap-throughs. Our feeds are interspersed with adverts and sponsored posts that have been carefully curated to maximise the potential click/tap-through rate of their victims. Soshana Zuboff defines this as arising from a 'market of human behavioural futures' (2019) in her book

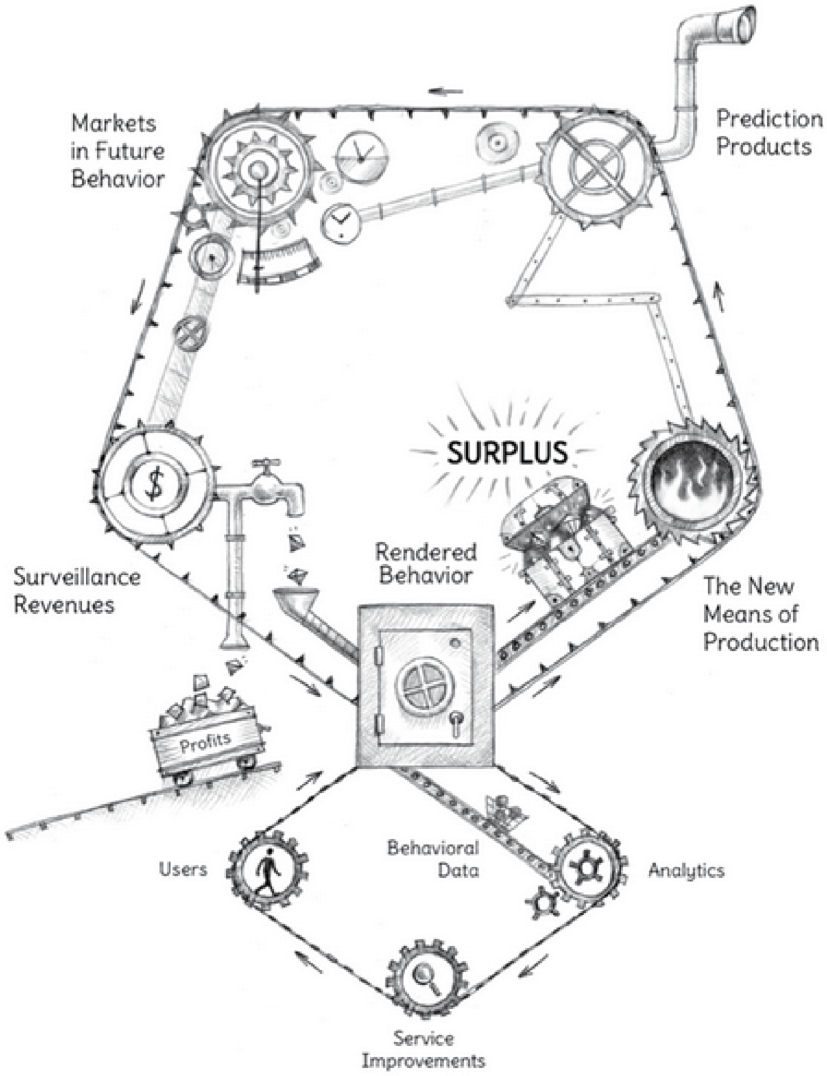


Figure 3.2: The Discovery of Behavioural Surplus (in Zuboff, 2019)

Surveillance Capitalism. Through this surveillance, large amounts of behavioural, affective, and personal data (termed behavioural surplus by Zuboff) are 'skimmed' off the top of our engagement with these platforms, and sold to agencies that match this personal data with products/content you are most likely to engage with. How could it be argued that that the production and consumption of art / content on such platforms is not governed by 'private gain' at our expense?

More recently, there are facets of the rise of non-fungible token (NFT) art projects that epitomise this continued fetishisation and veneration of digital fine art under the guise of 'decentralisation'. Unfortunately enough, these projects often fall foul to the exact 'centralisation' they market to oppose, creating small micro-communities of inter-centralised followers that collectively and actively, through social media, ensnare new and uninitiated retail investors via the urgency phenomenon of the 'fear of missing out'. The motivation being to increase

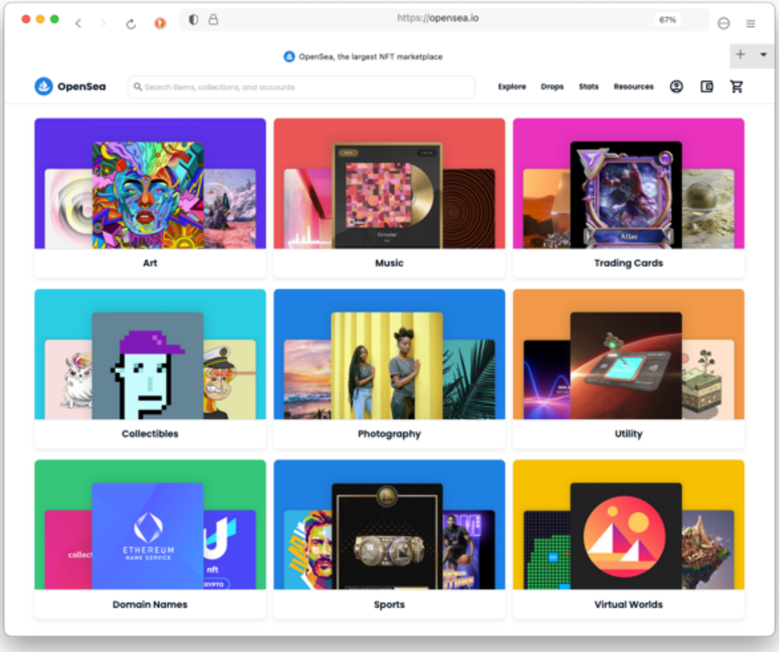


Figure 3.3: Categories of NFTs being sold on one of the largest NFT marketplaces (from OpenSea, 2022*a*)

the value of their own NFTs - sometimes referred to as 'shilling'. In some NFT projects, the only drive is profit motive, the digital art is merely the vehicle through which this investment is (im)materially realised. Despite the technological basis of some of these projects being quite radical in their proposition of democratic ownership and the privacy and security of digital information through decentralisation, the asset class some of them end up facilitating is tied to a a method of procurement and self-promotion that necessitates the enrichment of the creators and early adopters of that specific NFT collection. How, in any way, could this method of production and consumption be said to be different from Dewey's outlining of the rise of the 'nouveaux riches':

> 'The nouveaux riches, who are an important by-product of the capitalist system, have felt especially bound to surround themselves with works of fine art which, being rare, are also costly. Generally speaking, the typical collector is the typical capitalist. For evidence of good standing in the realm of higher culture, he amasses paintings, statuary, and artistic bijoux, as his stocks and bonds certify to his standing in the economic world.' (1934, p. 7)

It could be argued therefore, that we have witnessed an increase in the amount of new media formats, but not one that resituates production outside of capitalist logic for the masses; even in so called 'decentralised' projects. When Leddy and Puolakka stress that it is this 'private control of [the] forces of production for private gain' that leads to this disconnection of art from experience, it follows that the creation of art outside of the confines of this control addresses the imperative for the drawing of art 'from all sources' [own emphasis]. From this view, the convergence of digital art to their 'conditions of origin and operation in experience' could be seen as one of the primary foci of more recent movements such as Maker, Hacker, and DIY Labs, as well as the general ethos of participatory design and open-source hardware and software in art, design, and electronic music practice.

But what does it mean to say that art ought to originate and operate 'in' experience, and how might these movements address this? Dewey considers the 'live creature' in response to this question. He views the participant of aesthetic experience as meaningfully inseparable from the environment in which they are embedded:

> 'The senses are the organs through which the live creature participates directly in the on-goings of the world about [them]. In this participation the varied wonder and splendour of this world are made actual for [them] in the qualities [they experience]. This material cannot be opposed to action, for motor apparatus and 'will' itself are the means by which this participation is carried on and directed. It cannot be opposed to 'intellect', for mind is the means by which participation is rendered fruitful through sense; by which meanings and values are extracted, retained, and put to further service in the intercourse of the live creature with [their] surroundings.' (1934, p. 22)

From this basis, namely that perception, sensorimotor action, and intellect cannot be meaningfully separated when considering the intercourse of participants with their environment, Dewey highlights the weakness in the traditional dualist / cognitivist model - we are embodied and embedded beings. He posits that experience results from the 'interaction of organism and environment', and that in its fullest, experience can represent a 'transformation of interaction into participation and communication'. It would follow, therefore, that in the production of artistic works, consideration of this dynamical relationship that constitutes our subjective experiences is not only valuable, but that artistic works should aim to arise (originate) from common and relatable states of this relationship. Returning art to this origination and operation 'in' experience through interactive and participatory digital means can therefore be seen as a crucial mechanism for inducing positive societal change through fostering new channels of 'participation and communication'. Shifting the production of artistic work away from the exploitative practices of mass manufacturing inherent in consumer technologies, as well as centring embodied participatory design practices, is a common theme among DIY and Makerspace communities.

This is not to in any way demean or reduce the social importance of art that does not take these approaches. It is also especially tricky to prove in any certainty the subjective measures of aesthetic experience that could result in positive societal change. However, I do view the imperative to shift production and consumption of art outside the capitalist architecture of current proprietary software tools and consumer technologies, and bringing the aesthetic closer to every day experience as a fruitful endeavour for the artist. I argue that doing so would emphasise the dynamical relationship participants find themselves in with their and, crucially, others' sociocultural, economic, and ecological contexts.

Where does knowledge lie for us as researchers in the production and consumption of such artistic works? On what basis can we test and evaluate these claims? One view that is popular in the field of music technology is that of considering the nature of the interactive and digital systems that we develop; a consideration of the epistemic tool.

> 'The digital instrument is an artefact primarily based on rational foundations, and, as a tool yielding hermeneutic relations, it is characterised by its origins in a specific culture. This portrayal highlights the strengthened responsibilities on the designers of digital tools, in terms of aesthetics and cultural influence, as they are more symbolic and of compositional pertinence than our physical tools.' (Magnusson, 2009*a*, p. 335)

Developed by Magnusson, this line of thinking proposes that the digital instruments we design and employ as artists have inscribed in their physicality, affordance and sonic output, knowledge of cultural, historical, and designerly significance. In this way, they can be considered complex systems of research importance through the examination of their symbolic design, construction, performance, and appreciation by audiences. Magnusson embeds this proposition within Don Ihde's philosophy of 'instrumental realism' and Wittgenstinian philosophy, and draws from an understanding of the extended mind hypothesis. This theory, which will be expanded on in the next section, proposes that

> '[Under certain conditions], the human organism is linked with an external entity in a two-way interaction, creating a coupled system that can be seen as a cognitive system in its own right.' (Clark and Chalmers, 1998, p. 7)

Similar to Dewey's conception of how the live creature is inseparable from the environmental conditions that it is embedded in, the extended mind hypothesis and similar theories of embodied cognition prove to be invaluable in the field of tangible user interfaces, and DMI design, due to the way they can explicate as well as draw out the dynamic relationships between artist, collaborator, material, interface, and audience in the deployment of expressive artistic media. In the following sections, I shall dive deeper into these theories of embodiment, and what they have to offer a practice that makes use of AR technologies within the field of computational art and musical performance.

Figure 3.4: An early Halldorophone (cello-like feedback instrument) (from Úlfarsson, 2014)

3.3 The 4E Approach to Experience

One way of expanding on this conception of aesthetic experience is to adopt the an increasingly popular approach to conceptualising experience called enactivism. Key to my following theoretical underpinning of materiality, embodiment, and space will involve how this approaches the themes of perception, agency and cognition arising through the complex inter-threaded coupling between a participant and their environment. Often referred to as 'the 4 E's', 4EC, states that cognition is an *embodied*, *embedded*, *enactive*, and *extended* process (Gallagher, 2017). It's worth mentioning that 4EC is an amalgamation of theories across the disciplines of philosophy and the social and cognitive sciences, and as such there are different flavours of it. Many of these have said to have roots in the Dewey's (among others') pragmatism outlined in the previous section, as well as Merleau-Ponty's embodiment theories (Zavota, 2016). What these constituent theories all bear in common is the rejection of the standard cognitivist model of experience that states that cognitive processes happen solely 'in the mind' and 'in the brain'. Another principle is that they generally draw from complex systems theory: 'understanding the complex interplay of brain, body and world requires the tools and methods of nonlinear dynamical systems theory' (Clark, 1999). Before delving into the specification and implications of a 4EC approach, I would first like to touch on this concept of complexity, as it will surface throughout the thesis. Within certain systems, which are deemed to be 'complex', this field proposes that there are a multitude of phenomena that can explicate the interactions between components of such a continually unfolding system, including (De Domenico and Sayama, 2019):

- Interactions - a complex system is formed of many components, many of which will be connected in a network of mutual and on-going interaction
- Emergence - from this network of interactions, there exists the possibility for complex and novel structures to form that are inexplicable from the features of their simpler components
- Dynamics - the state of a complex system can change over time, often in an unpredictable non-linear fashion
- Self-organisation - the components of a complex system may exhibit collective behaviours, and perceived large scale structure
- Adaptation - complex systems don't necessarily shift between steady states, they actively and reactively respond to environmental stimuli
- Feedback - structures of a complex system exhibit a phenomena where the outputs of a system are routed back in, via closed chains of cause and effect

Figure 3.5: Starling murmuration displaying complex and emergent flocking behaviours (taken by Kentish, 2020, in Brighton, UK)

Thus, 4EC normally begins with an acknowledgement of the complex embodied nature of human cognition. Varela, Thompson, and Rosch propose that cognition is embodied in a way not too dissimilar to the assertion Dewey holds in regards to the 'senses' of the 'live creature'.

> 'By using the term embodied we mean to highlight two points: first, that cognition depends upon the kinds of experience that come from having a body with various sensorimotor capacities, and second, that these individual sensorimotor capacities are themselves embedded in a more encompassing biological, psychological, and cultural context.' (1993, pp. 172-173)

Alva Nöe's concept of sensorimotor contingencies has since built on the first point of this approach to embodiment, in a way that proposes an 'enactive approach to perception' accepts that perception is something we do, not something that happens to us (Noë, 2004). This has since been termed the 'sensorimotor approach' to enactivism, and Gallagher notes that it falls short of an 'enactivist approach' due to its omission of affective aspects of embodiment such as 'mood-related and emotional factors, [...] bodily states such as hunger, fatigue, and pain, as well as a complex motivational dimension that animates body-world interaction' (Gallagher, 2017, p. 150) The proposal is that that an 'enactivist' approach, i.e. one that aligns with Varela, Thompson, and Rosch's claim that sensorimotor capacity is 'embedded in biological, psychological, and cultural contexts' more holistic perspective, the proponents of embodiment theories of 4EC propose a radical shift from the standard cognitivist model; sensory perception and bodily existence is not only causally related to the emergence of cognitive processes, it literally constitutes them.

A natural continuation extends this line of reasoning to the material environment in which the participant is a part of — accepting that it is in turn shaped by the web of sociocultural norms and values that Dewey alludes to, and is the site of sensorimotor action. Mark Rowlands proposes this underlying thesis as 'the embedded mind':

> 'In accomplishing cognitive tasks, an organism can utilize structures in its environment in such a way that the amount of internal processing it must perform is reduced. Some of the complexity of the task is, thereby, off-loaded onto the environment, given that the organism has the ability to appropriately exploit that environment.' (2010, p. 68)

It necessarily follows that if a cognitive system that has the potential for environmentally embedded sensorimotor action, i.e. it is embodied and embedded, it also enacts its cognition. The first formal account of what could be called an enactive approach to cognition begins also in

'The Embodied Mind', by Varela, Thompson and Rosch. From a foundation of accepting that sensory and motor processes, namely perception and action, are 'inseparable in lived cognition', enaction is contingent on two assumptions: perception consists in perceptually guided action, and cognitive structures emerge from the recurrent sensorimotor patterns that enable action to be perceptually guided (1993, p. 173). The authors argue that an enactive approach to cognition therefore proposes that perception must be studied from the point of view of the participant's sensorimotor structure, rather than any 'pre-given, perceiver-dependent world', i.e. the world is not perceived through an internal representational model of what is 'outside', rather, the world emerges from a participants ability to 'guide [their] actions in [their] local situation', to enact.

The last assertion of a 4EC account claims that cognition has the potential to be extended into objects in a participants environment. The extended mind hypothesis, as developed by Andy Clark and David Chalmers and described in the previous section, is the core thesis of this proposal. The authors propose that, cognitive processes, beliefs for example, can be 'constituted partly by features in the environment, when those features play the right sort of role in driving cognitive processes' (1998, p. 12). They compare the experience of cognition in two different hypothetical people, Inga and Otto. Both are tasked with recalling the address of the MoMA and travelling to it. Inga has a neurotypically functioning memory, and so accesses the memory of the address (which assumedly lay dormant previous to this action) recalls it, and travels to the address. Otto has Alzheimers, and like many others with Alzheimers relies on the use of a notebook or memory aid to recall experiences and other important information, he finds the address in the notebook, and travels to the museum. In both cases, Clark and Chalmers propose that the cognitive functionality of what constitutes 'belief' are analogous:

> 'To say that the beliefs disappear when the notebook is filed away seems to miss the big picture in just the same way as saying that Inga's beliefs disappear as soon as she is [no] longer conscious of them. In both cases the information is reliably there when needed, available to consciousness and available to guide action, just the way that we expect a belief to be' (1998, 13).

It therefore follows, that cognition is extended, beyond the boundary of the mind-body and into the environment, and even into specific artefacts - a key theory that enables the proposition of Magnusson's epistemic tool within the field of music technology, as mentioned previously. Taking these four points of departure, namely that cognition is embodied, embedded, enacted, and extended, Gallagher presents the following assumptions as the core conditions of an enactivist approach to cognition (Gallagher, 2017, p. 6):

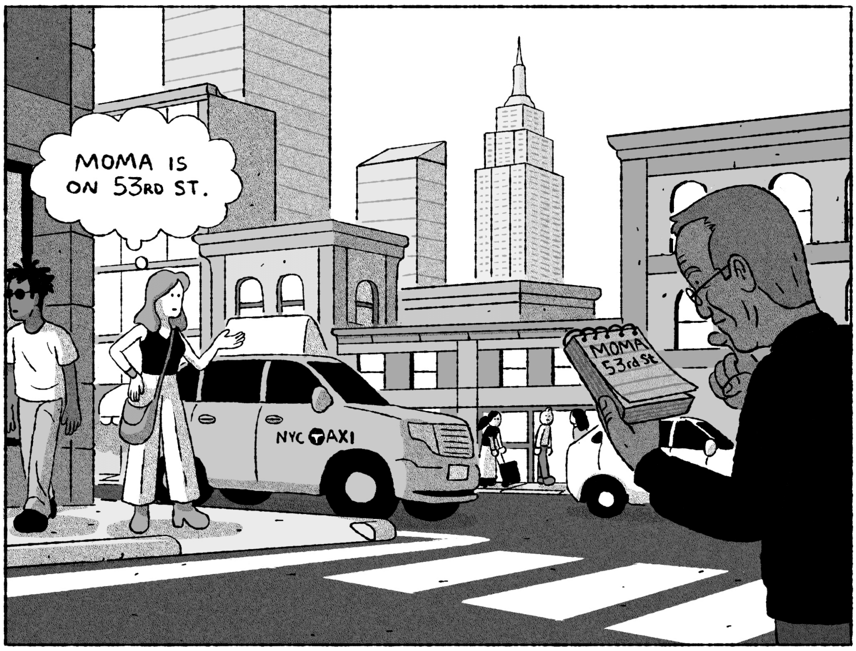


Figure 3.6: Inga and Otto on their way to the MoMA (by Tim Peacock in Chalmers, 2022)

1. Cognition is not simply a brain event. It emerges from processes distributed across brain – body – environment. The mind is embodied; from a first-person perspective embodiment is equivalent to the phenomenological concept of the lived body. From a third-person perspective the organism–environment is taken as the explanatory unit.

2. The world (meaning, intentionality) is not pre-given or predefined, but is structured by cognition and action

3. Cognitive processes acquire meaning in part by their role in the context of action, rather than through a representational mapping or replicated internal model of the world

4. Enactivist approaches have strong links to dynamical systems theory, emphasising the relevance of dynamical coupling and coordination across brain – body – environment

5. In contrast to classic cognitive science, which is often characterised by methodological individualism with a focus on internal mechanisms, enactivist approaches emphasize the extended, intersubjective, and socially situated nature of cognitive systems. Enactivism aims to ground higher and more complex cognitive functions not only in sensorimotor coordination, but also in affective and autonomic aspects of the full body.

6. Higher-order cognitive functions, such as reflective thinking or deliberation, are exercises of skilful know-how and are usually coupled with situated and embodied actions

Poignantly, this way of framing our human experience is salient for the digital humanities at this point in time. More of our everyday social, artistic, political, cultural, environmental, and economic interactions are mediated by technologies and platforms. These are privately owned by mega-corporations, that as previously mentioned, have shown dubious a relationship with ethics concerning misinformation and user privacy, as well as extractivist methods of guaranteeing shareholder profit. Does Facebook's 'metaverse' sound like the kind of AR environment that sounds like a safe and democratic ground for art that seeks the 'transformation of interaction into participation and communication' (Dewey, 1934)? This decision is up to the reader, but I would argue not as it will become clear in the following sections.

Out of this model of explicating experience, I propose three lenses through which to examine AR applications in the sonic arts - materiality, embodiment, and spatiality. In some ways, a linear, written account of these processes, separated neatly by subheadings is somewhat incompatible with the logic of 4EC and its process-inseparability, nevertheless, in the following sections of this chapter I will attempt to go into detail how we can use this model of experience, to consider the themes of materiality, embodiment, and space within AR musical instrument research practice, as well as the broader study of digital humanities. Loosely, these three sections will cover the artistic, audience, and societal considerations and potentialities respectively, when engaging with AR systems.

3.4 Complex Material in Interactive Music Systems

Thus far, we have outlined the contextual origins of AR technology, as well as their contemporary physical forms, modes of sensory display, and methods of real and virtual processing. Additionally, I have outlined the theories of aesthetic and perceptual experience through which these technologies could be interrogated to further understand AR's role as a medium for artistic expression. In this section I will propose a lens through which to consider the artist's composition of 'material' in AR experiences as a method of fostering a modulated dialogue between elements of a participants sensorimotor engagement with their perceived real and virtual environment.

Existing frameworks for considering the design of relationships between real and virtual processes do exist within in the field of AR; in the early 90's, the theoretical work of Milgram and Kishino, their reality-virtuality continuum (1994, p. 10), proved to be a fruitful way of sorting the types of AR and VR technologies that were arising from different fields at the time. However, for my purposes of detailing the material nature of an artists' composition in AR, a more nuanced and detailed framework is needed, one that goes beyond specifying the what (a spectrum of reality to virtuality); towards a investigating of the how, (a processual space of augmentation, diminution, alteration, hybridisation, and extension through which real and virtual environments are enmeshed), and the why (the conveyance of meaning and intentionality of the artistic work).

Hanna Schraffenberger, as highlighted in Section 2.5, offers a set of relations that describe the dynamics between 'the virtual and the real' (see Table 2.1, 21). She argues that from the fundamental relationships of presence, information, physicality, and behaviour, there emerge new 'subforms' of AR, namely extended, diminished, altered and hybrid reality, as well as extended perception. Yet, even with this level of description, the processes themselves are still abstract - these are descriptors for the types of processes, but what are the processes themselves? I believe that the answer lies again, in an approach aligned with complex systems theory; through a consideration of phenomena such as interaction, emergence, dynamics, self-organisation, adaptation, and feedback.

Within the field of music interfaces, considerable research and practice has been conducted in the area of complex systems. Surmised neatly by musical interface researcher Joel Ryan, hidden, or black-boxed complex processes within digital interfaces can be developed and explored through ascribing 'physical handles' to these 'phantom models', e.g. providing embodied interaction to algorithmic musical processes to better understand, design, and evaluate them.

Figure 3.7: Atau Tanaka performing *Myogram*, an 8 channel sonification of muscular corporeal states (taken by Delaney, 2017)

> 'The physicality of the performance interface helps give definition to the modelling process itself. The physical relation to a model stimulates the imagination and enables the elaboration of the model using spatial and physical metaphors. The image with which the artist works to realise his or her idea is no longer a phantom, it can be touched, navigated and negotiated with.' (1991, p.5)

Perhaps the design of AR musical instruments is concerned with not only providing physical handles to phantom models, but phantom handles to physical models too.

In the same vein, Agostino Di Scipio outlined his perspective on the paradigm of interaction in the context of audio signal processing and musical interface use.

> 'Interactive music systems are dedicated computational tools capable of reacting in real time, upon changes in their 'external conditions', [typically including] initial input data and run-time control data [...] set, changed and adjusted by some agent – a performer, or group of performers [...] Control devices, with their mechanical and/or visual interfaces, are operated to determine these data.
>
> The main purpose of control data is to determine a system's changes of internal state. This is done indirectly, by updating the parameters in either digital signal processing techniques or program routines operating at a more abstract, symbolic level. Changes of internal state are heard as changes in the musical output. By operating the available control devices, the agent in effect 'plays' the system as if it were a new kind of music instrument' (2003, p. 1)

For Di Scipio, the act of integrating the agent / performer into the definition of the music system implies that 'interaction' exists in the 'underlying ontology' or 'interdependent coupling' of participant and instrument; at the site of their 'interface'. This coupling creates linear feedback loops in performance, between the resultant sound, and decisions made by the performer. Indeed, this lower-level dependency (human-machine) itself exists within the wider 'meta-system' including '[human], machine and environment'. Within this meta-system, later referred to as an 'ecosystem', Di Scipio outlines that:

> 'A principal aim would be to create a dynamical system exhibiting an adaptive behaviour to the surrounding external conditions, and capable to interfere with the external conditions themselves. Not only would it be able to detect changes in the external world and 'hear' what happens out there, [...] it would also be able to become a self-observing system, that is, to determine its own internal states based on the available information on the external conditions – including the traces of its own existence left in the surroundings. [...] This [move towards composing musical interactions] should be described as a shift from creating wanted sounds via interactive means, towards creating wanted interactions having audible traces. In the latter case, one designs, implements and maintains a network of connected components whose emergent behaviour in sound one calls music.' (2003, p. 6)

The depth of research based on this type of complex interactive music system (IMS) has deepened considerably in the last 20 years, as artificial intelligence and machine learning algorithms, low-latency microcontrollers, and real-time compositional software have been implemented into what Magnusson terms 'intelligent instruments' (2009*b*, p. 8). Thus, 'performative ecosystems' (Waters, 2007) such as these exhibit behaviours of complex systems as mentioned above, including interaction, emergence, dynamics, self-organisation, adaptation, and feedback. I propose therefore that an enactivist approach to experience 4EC, one that posits the emergence of cognitive processes across the distributed system of mind-body-environment as being wholly appropriate in the design, creation, performance, an evaluation of interactive music ecosystems.

Figure 3.8: Bowed Cardboard Box in performance *Cardboard Cutout* (from Green, 2010)

Some of the first proponents of this approach include Essl and O'Modhrain, who propose an enactive approach they term 'weak sensorimotor integration' to the design philosophy of tangible interfaces for musical expression. 'What concerns us here[...], is the consideration of enactive knowledge in the context of musical instrument design and how perceptually guided action defines the 'feel' and playability of a musical instrument.' (2006, p. 3). Core to their research is the question: 'In what way does a specific integration of sensory perception and motor action correspond to a controllable, even enjoyable musical performance experience?' Building on the class of expected sounds that correlate to our action with physical objects in the world, Essl and O'Modhrain evaluate the design of a set of prototype tangible interfaces that introduce a flexibility in this expectation-realisation coupling between action and sound by altering the digital sonic output of the system based on measured user interaction. They propose that the resultant interaction with these instruments provided grounds to include a loose sensorimotor integration into the design of musical interfaces. The present thesis is interested in the implication of this hypothesis in the creation of not only physical interactions with IMS, but also virtual, and ultimately, hybrid interactions. My own 4EC approach to the compositional material of AR musical experiences draws from Essl and O'Modhrain's own motivation for their proposal of an enactive approach. How are dynamics of AR musical systems learnt over time? How is the ability to predict musical outcomes affected by the integration real-time motion sensing and parameter mapping? How does the configuration of hybrid sensory content define the way action becomes perceptually guided?

Newton Armstrong also provides considerable insight on the enactive design of DMIs. He proposes an 'enactive model of interaction' that is concerned with 'circular chains of embodied interdependency between performer and instrument, instrumental 'resistance' to human action and intentionality, and an integrative approach to the roles of sensing, acting and cognitive process in the incremental acquisition of performative skill.' For Armstrong, this approach draws from a principled distinction between 'functional' and 'realizational' interfaces. Whereas a functional interface 'serves a predetermined function; it is structured around a finite set of interactions which are known in advance of the task's execution', a realizational interface 'brings with it the possibility of continuously realizing new encounters and uses, and, in the process, of re-determining the relationship between technical objects and their human subjects' (Armstrong, 2006, p. v). This distinction, and a pursuit of the latter over the former, means to prioritise the contexts of 'meaning and signification in which human and medium are embedded, and is conducive to dynamic and indeterminate forms of interaction' (p.42). These dynamic forms of interaction are realised through performer intention, and instrumental 'resistance' in response the performer's engagement with it. Over time, this resistance establishes adaptation in participant interaction, constituting what Armstrong terms a 'dynamical responsiveness' between the performer and their instrument (pp.46-47).

Figure 3.9: *Moon via Spirit* by Lauren Sarah Hayes in performance (taken by Slater, 2019)

Lauren Sarah Hayes' work approaches live electronic music practice from an enactive and embodied perspective. This work often uses tangible and haptic controllers that provide non-linear controller input to various elements of the 'ecological network of sound analysis and digital signal processing' that constitutes her performance ecosystems. For Hayes, designing complex and adaptive musical systems allows 'elements of instability, vulnerability, unpredictability [to] become fodder for the improviser' (Hayes, 2018, p. 2). Hayes' creative and research practice has enabled a pedagogical methodology, in which 'music and movement-based improvisational practices' are explored in classes of undergraduate students. Through a combination of deep listening methods, movement exercises, and free improvisational exercises, Hayes argues that there is a potential for co-creation of compelling improvisational performances in classes of up to thirty untrained improvisers. These techniques result not only in the active exploration of musical sensorimotor contingencies, but also in the creation of musical meaning that is 'brought forth through an emergent extended cognitive network that involves complex relationships between the improvisers involved, technology, and the space in which the performer-instrument pairings are distributed' (Hayes, 2019, p. 8). These ensemble improvisations draw from a wide variety of media formats including AR. Pointing towards the following assertion by Schiavio and van der Schyff (2018), Hayes notes that digital musical instrument practice ought to develop and augment improvisational practices 'that build collectively on individual musical and creative sociocultural histories that individuals bring to the table':

> 'If the body plays a key role in determining musical learning, so does the socio-material and cultural environment in which it is embedded. However, these dimensions are not separated from the body. Rather, they become manifest through the body and are co-determined by actions and interactions with other bodies and things in socio-culturally meaningful contexts.' (Hayes, 2018, p. 9)

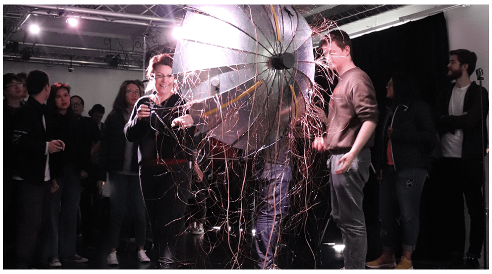


Figure 3.10: Multiple participants engage with Listening Mirrors (from Chevalier and Kiefer, 2019)

Chevalier and Kiefer propose a similar method of promoting musical expression in their AAR work 'Listening Mirrors' (2018). Their is system is 'audience participation dependent', and could constitute a realisational DMI. Through real-time analysis and re-projection of participants' breath and vocal sounds via bone-conduction headphones and a transducer-augmented parabolic mirror, audience members, environment, and interfaces 'feed off each other', co-creating physical and virtual sound environments that overlap and co-construct a shared hybrid listening space. Their creative and research practice is situated in the later work of Merleau-Ponty and related theories of enactivism. In particular, Chevalier draws from Merleau-Ponty's notion of the 'flesh':

> 'In defining what is meant by 'flesh', Merleau-Ponty states, '[w]e must seek space and its content together', that we are 'interwoven into a single fabric', a 'universal flesh', and 'he who sees cannot possess the visible unless he is possessed by it, unless he is of it'. The notion of 'flesh', therefore, is both the 'flesh of the world' and the 'flesh of the body', the relation of the corps sauvage and cultural world and its representations.' (Chevalier, p. 58, (2016) citing Merleau-Ponty, (1945; 1968))

Thus, depending on the specific artwork, from any or each of the DMI designer's (Essl and O'Modhrain, 2006; Armstrong, 2006), improvisational performer's (Hayes, 2019), or installation artist's (Chevalier and Kiefer, 2018) perspective, if the material composition of the system with which they are engaging is designed to provide a realisational, dynamic interaction then it 'assumes open-ended, fluid, and at least partly indeterminate processes of signification, and as such requires the ongoing cognitive involvement of the musician' (Armstrong, 2006, p. 48). This necessity of engagement aesthetically situates such artworks and instruments closer to the site of everyday embodied life, what Dewey terms the return of art to its 'origin and operation' in experience. These examples also align themselves with the 4EC approach to experience, which argues that cognitive process are embodied, embedded, enacted, and extended, across a distribution of mind - body - environment. Readers interested a more comprehensive theoretical and scientific investigation of dynamical systems, embodiment, and computer music artefacts may be interested in David Pirrò's thesis, 'Composing Interactions' (2017).

Augmented reality, specifically due to its ability to mediate perception in real-time and across a multitude of sensory modalities, presents the opportunity to 'experiment with, modulate and disrupt [conditions of situated-ness, timeliness, emergence, multimodality and engagement inherent to our embodied coupling] to create new audience collective experiences' (Chevalier and Kiefer, 2018)

3.5 Enactivist Approaches to the Body in XR Systems

We started this chapter with an examination of John Dewey's account of the separation of art from everyday life, and the effect on it thereof. To account for the notion of an aesthetic experience in the appreciation of artistic works, Dewey points towards the 'live creature'. This concept, as discussed, contributed to the modern study of 4EC: the notion that cognitive processes ought to be thought of as embodied, embedded, enactive, and extended across the distribution of brain-body-environment. The previous section outlined my approach to material composition from an artists perspective. The medium of AR may be thought of as an 'performance ecosystem constituted of relationships between real and virtual processes'. The present section moves forward to consider the experience of participants in such artworks.

3.5.1 Embodiment and Enactivism in VR

Considerable amounts of research related to embodiment in the context of VEs generally falls under specific but necessary discussions and measurements of particular cognitive and affective processes such as presence, emotion, awareness, and consciousness (Slater et al., 1994; Seth et al., 2012), for example, in body swap experiments (Slater et al., 2010), the rubber-hand illusion

(Suzuki et al., 2013), and stimulating altered visual phenomenology (Suzuki et al., 2017), as shown in Figure 3.11. Integration of explicitly 4EC approaches to VEs / VR have only started to appear in research in the last 10 years, and is generally lacking from the discourse around AR. For example, through an two and a half year autoethnographic exploration of her own experience in the popular VE Second Life, Maeva Veerapen integrated the phenomenological theories of Merleau-Ponty and Husserl to analyse and explicate the specific location of 'embodiment' inherent in the connection to her virtual avatar. She surmised that 'such an experience is still anchored within the user's physical body and that its relation with the avatar's body creates the link between the two spaces, physical and virtual' and termed this state of being *symbembodiment* - symbiotic embodiment of a combined real and virtual self (Veerapen, 2011).

Figure 3.11: Google DeepDream providing (non-realtime) altered visual phenomenology of Sussex campus via VR playback (from Suzuki, 2017)

Drawing on Veerapen's notion of *symbembodiment* and linking it to an enactivist approach (indeed, as Varela, Thompson, and Rosch state in their 'The Embodied Mind', Merleau-Ponty and Husserl's theories form part of the Western phenomenological roots of their approach (1993, pp. 173, 18)), Willans et al. argue that the 'episodes of emotion' in the experience of VEs are linked with feelings of 'presence', which in turn emerges from the embedded nature of a participants sensorimotor structure, or, we might say, enaction (2016, p. 23). Hovhannisyan et al. argue for an enactivist approach to understanding participant flow, which is motivated by the authors' resistance to the physicalist approach to designing 'object-centred' VR experiences that is typically employed (2019, p. 1). In particular, they turn attention towards what they call an action-predicated perspective (one that focuses on the enactivist theory of perceptually guided action) that they state is 'non-reductive with respect to subjective experience', and honours 'the pragmatic dimension of perceptual reality' (2019, p. 18).

3.5.2 Embodiment and Enactivism in AR

Within AR, Riva et al. propose that AR and VR can transform our 'external experience' through the increased levels of presence and engagement they afford, that in turn generates 'personal efficacy and self-reflectiveness' (2016, p. 10), they further propose that it has the potential to do the same for our 'internal experience' . For the authors, 'bodily self-consciousness' can be enhanced and extended by altering/extending its boundaries through a process called ’augmented embodiment’ , which builds on the hypothesis that embodiment could be altered, expanded, and distributed through AR technology:

> ‘Whenever computer-based information is blended with the perception of the surrounding physical world, as in augmented reality this may become integrated into a new form of altered embodiment. But that requires that the augmentation of the physical with the virtual be carried out in such a way that the user has the potential to feel present. Given the clear popularity of mobility and social connectivity, it seems that presence will increasingly be experienced through attention to an external world in which the physical and the virtual are somehow blended’ (Waterworth and Waterworth, 2014)

From an 4EC approach, ‘feeling present’ in the context of bodily ‘mobility and social connectivity’, emerges, and could be seen to be somewhat analogous with, the notion of action (and other cognitive processes) being embedded in the socio-cultural and -material norms and values of a participant’s environment, their inherent sensorimotor embodiment, and as a result, the propensity for their actions to be perceptually guided (enaction). Suzuki et al. operationalise Nöe’s (2004) concept of sensorimotor contingencies, as further developed by Seth in the field of predictive processing (2014), by using AR/VR technology as a test-bed for exploring the effect of modulated sensorimotor contingency and congruency in participant’s visual experience of familiar and unfamiliar 3D objects (Suzuki et al., 2019). Their results indicate that ‘that the contingency, but not the congruency, of a person’s actions and their visual consequences influences access to visual awareness’, providing support for a 4EC-like perspective on perception (and also hinting at the ability for AR technology to be used as a method for purposeful sensory illusion through sensorimotor incongruence). Most recently, Chalmers has argued that AR has the potential to extend our mind in a more seamless fashion, in a way that he likens to Heidegger’s proposal of the ‘ready-to-hand’ nature of certain tools; in use they become an extension of our body without our having to ‘think’ about them and the actions they afford.

> ‘What sort of mental processes do augmented reality devices extend? For a start, they can more seamlessly extend all the processes that smartphones extend: memory (remembering someone’s birthday), navigation (getting to the museum), decision-making (deciding where to eat), communication (talking to friends), language processing (translating from another language), and more. But their immersive connec-

tion to our perceptual system provides new avenues for extension' (Chalmers, 2022, p. 299)

Chalmers further proposes that AR provides the grounds for further cognitive extension: our abilities of perception (e.g. through infra-red sensing), recognition (through algorithmic processing and machine learning of real-time environmental data), and imagination (through real-time replacement or transformation of physical objects with virtual ones). Considering Ishi and Omar, – Inga and Otto's 21st century counterparts – in Figure 3.12, Chalmers shows that AR devices can theoretically provide cognitive extension, vis-a-vis 'The Extended Mind'.

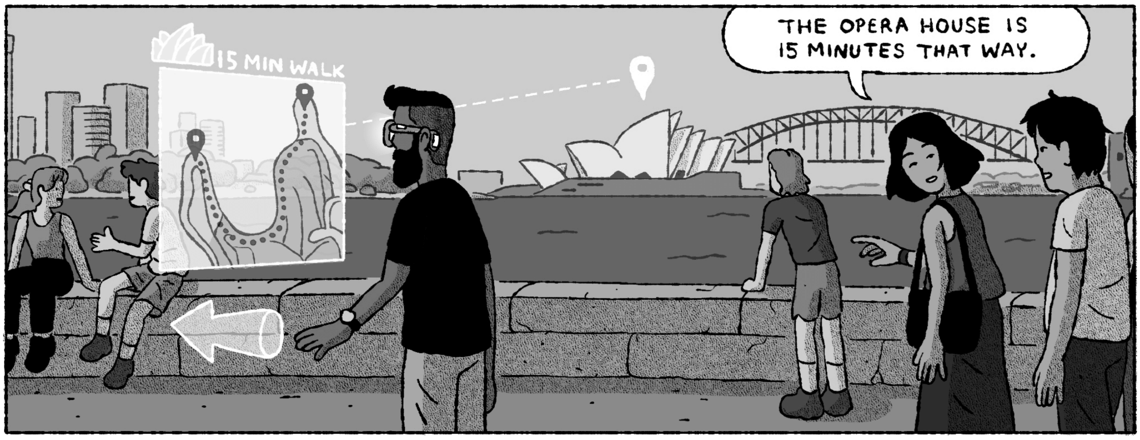


Figure 3.12: Ishi and Omar on their individually recollected routes to the Sydney Opera House (by Tim Peacock, in Chalmers, 2022)

3.6 The Elephant in Our Headsets: The Zuckerverse

As we have established so far, AR, when applied as a medium for the composition, performance, and expression of multisensory art and music, has the potential to:

1. Provide new modes of instrumental performance and expression to performers and participants
2. Radically modulate the embodied experience of performers and participants
3. Scaffold new musical and artistic meaning through these augmented aesthetic experiences

It follows that such experiences appropriate existing physically real spaces to do so, whilst either (a) simultaneously creating a relational virtual space dependent on the content of the experience, or (b) appropriating physically real spaces to the ends of constructing an entirely new hybrid AR space that is greater than the sum of its physical and virtual counterparts. In current popular culture, this notion of a type of physical and virtual hybrid space has been given the term (the) 'Metaverse'.

'The Metaverse' gained popularity as a term partway through this writing thesis, partly due to Facebook's calculated re-brand to Meta, partly due to the resulting 'bull' run in 'metaverse' cryptocurrencies, and partly due to the large subsequent increase of venture capital funding in XR start-ups. The reality is however that it is not a new term, having originated from Neal Stephenson's *Snow Crash* (Stephenson, 1992), a sci-fi novel detailing an anarcho-capitalist future in which a VR-based internet (The Metaverse) has become the gamified site of socio-cultural and economic norms, values, and interactions. In textitSnow Crash, Metaverse users immerse themselves via personal or publicly available terminals (see VR), although using public terminals has a negative affect on your avatar appearance and thus your status in The Metaverse.

Though perhaps tangential to, rather than aligned with, the motivations and political thought contained in Stephenson's work, *Snow Crash*, and other novels by him, have influenced Silicon Valley tech oligarchs such as Bill Gates (Microsoft), Jeff Bezos (Amazon), Sergey Brin (Google), John Carmack (Oculus, now owned by Facebook), and Peter Thiel (PayPal, and first external funder of Facebook) (Rogers, 2021). One of the auxiliary aims of this chapter is to ask, 'with regards to the unfolding corporate metaverse, is theirs a morally just pursuit?' mainly through the question 'should we be willing immersants of their techno(dys/u)topian dream?'. Broadly speaking, the definition of 'the' Metaverse has since expanded to contain any sufficiently 'immersive web3.0' interaction or XR experience. As sound-artists and musicians, this necessarily ushers **any** AR experience we may be composing, performing, or developing under the umbrella term 'Metaverse'. Hence, we ought to be aware of the 'landscape' so to speak. Do we want our artwork to be associated with this space, or is it tangential to our aims and desires as artists?

Most of these amalgamated definitions are still based in techno(dys/u)utopian ideals of the cybernetic man. This isn't surprising; the technologies the Metaverse makes use of, (AR, VR, satnav) lie 'deep within the military and Western - scientific - industrial - patriarchal complex' (Davies, 2004). A result of this is a paradigm that is also found in *Snow Crash*: the unregulated (see neoliberalism) pursuit of acquiring or constructing virtual 'land' or commodities only then to rent/sell it to either smaller corporations, or directly to the individual's drive for commodity accumulation through property and material ownership. This is a needless relationship and is already enacted in the present-day 'metaverse', and it is helped by the appropriation of XR development and experiences as a 'use case' or 'value proposition' for Blockchain and cryptocurrency:

> '[Living in the metaverse means] having a place to call home, where you can show off your possessions and maybe even have friends over' (own emphasis) (Marr, 2022)

As mentioned in Section 3.2, cryptocurrency, and NFTs are the current landscape on which, more broadly, digital art is being appropriated to increase the price of cryptocurrencies – through rare artworks, in-game item collectibles, and limited-edition music albums. It is the specific method of artificial scarcity to achieve wealth procurement that is needless. Even in non-crypto Metaverse spaces, the key holders tend to be large corporations, Facebook for example. Unfortunate as this all may be for us 'consumers', it is for the betterment of the bottom line of tech oligarchs, and early cryptocurrency adopters - and there must be business as usual. As artists it has fallen to us to propose alternative routes to accessible, diverse, and meaningful digital experiences to catalyse social change.

But the wider implications are even more astounding, beyond the dissemination and consumption of artistic works, even Stephenson's version of 'Metaverse' is already here, vis-à-vis virtual land ownership. Many argue it started with Second Life in 2003, but today, cryptocurrency projects like Decentraland, Sandbox, and Somnium Space, as well as corporate efforts like Meta Horizon Worlds, Workrooms, and Home (by Facebook) are the logical conclusions of those early progenitor VEs, when it is taken into consideration the lack of regulation around 'Big-Tech' and cryptocurrency platforms in general:

> 'Republic Realm [now Everyrealm] paid a record $4.3 million for land in the largest metaverse real estate platform, Sandbox. The company is developing 100 islands, called Fantasy Islands, with their own villas and a related market of boats and jet skis. Ninety of the islands sold on the first day for $15,000 each and some are now listed for resale for more than $100,000.' (Frank, 2022)

This article also mentions that despite $500,000,000 having been spent in 2021 on virtual land on platforms like The Sandbox, average land prices have decreased 91% over the last 9 months since their peak in early December 2021, which occurred 1 month after Republic Realm's purchase of $4.3 million (Kane, 2022). How much of that 'property' was bought by or let to retail investors hoping to become rich off of hard-earned savings, only to see 91% depreciation in their virtual asset?

What I hope to highlight in this section is that the 'metaverse' is not what it is portrayed as. Its current co-option by (or perhaps origination in) the profit motive inherent to cryptocurrency-based metaverse platforms does not 'liberate art', rather can lead to unenjoyable (De Jesus et al., 2022; Delic and Delfabbro, 2022), exploitative , and hyper-commercialised practices (Ledesma, 2021; Ongweso Jr., 2022; Gach, 2022). My criticism of these platforms is not to say that a diversity of media experiences, hosting a multiplicity of sociocultural narratives, from a variety of voices isn't welcome; rather the opposite. XR technologies, AR specifically, due to its material and embodied relations, propose a real potential to provide a type of embodied artistic liberation. But as Leddy and Puolakka note on Dewey Aesthetics Section 3.2, this liberation will never happen under the unchallenged constraints of the capitalist modus operandi. Thus, for as long as both mega-corporations and cryptocurrency is are drivers for use of 'space' in 'the Metaverse', it will always mirror these conditions and be inherently flawed. Yet if we are to believe the marketing speak, it is in 'spaces' like these that technology companies foresee cultural production shifting to and flourishing in the next 10 years (Fatemi, 2022). Although nascent in their implementation, and not widely known about, thankfully, mechanisms exist (see the Fediverse) to host open-source, federated communities away from the clutches and algorithmic abuse of 'Big-Tech'. Until that happens in earnest, it leaves us wondering... *What affect will the 'Metaverse' have on the production, consumption, and dissemination of art of all types?*

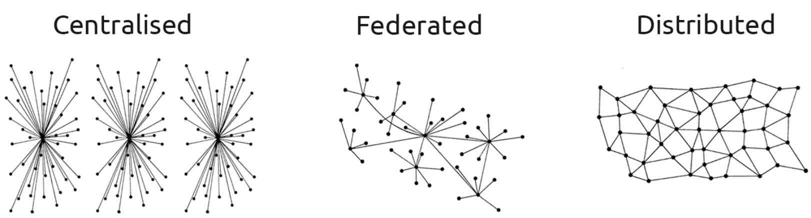


Figure 3.14: Different communication network types (in Baran, 1964)

Figure 3.13: An example of a rare *Fantasy Island* NFT (from Everyrealm, 2022)

In the next chapter I will outline the approach I have taken in my practice-based research to resist the current conception of 'XR work *as* the Metaverse'. This includes several forms of resistance, developing a DIY practice, creating and iterating on openly shared AR experiences, and developing a set of design patterns to aid artists and musicians in employing AR as a medium for creating similar work.

Part II

AUGMENTED INTERVENTIONS

4 A DIY Approach to AR in the Sonic Arts

Our environment is not a play, a performance in which only minor modifications are possible. It's an improvisation,[. . .] the nature of the interaction is radically open.

(Vermeulen, 2015)

4.1 Summary

In Chapter 2, the historical origins, contextual trends, exceptions, and contemporary forms of AR technologies were outlined. Additionally, examples of AR's use in the arts were provided, along with specific rationales for their use, e.g. sensory engagement, collaborative expression, and activism and agency. A positionality was established that demonstrates that AR's use in the arts is at odds with its origination in military and industrial applications. In the Chapter 3, I outlined a trio of lenses through which we may begin to consider the material, embodied, and spatial aspects of sound art using AR. In examining complex musical material, it was identified that digital musical systems or 'performance ecosystems' offer us fertile conceptual ground for description of material, in the creation and evaluation of rich experiences. The work of researchers approaching experience from an enactivist perspective when working with XR technologies was then outlined. Finally, an examination of the current state of the 'Metaverse' as a space to describe XR experience in general was critiqued. These three lenses all drew from an understanding of art *as* experience, and the disconnection between art and everyday life, an alienation that comes as no surprise given its commodity fetishisation by free-market capitalism. Moreover, the lenses were contextualised within a 4EC approach to experience, which posits that cognitive processes are embodied, embedded, enacted and extended; inseparable from the brain-body-environment that they constitute and are situated. In the current chapter I will be outlining my methodological approach that has informed both the theoretical, and practical sides of the research: designing, performing, and evaluating sound art AR experiences (*sound ARt* to borrow from Rhodes (2018)). A review of the outstanding research questions will be outlined, to provide the chapter a clear direction into the ensuing three study chapters.

3. What are AR's boundaries and affordances as a medium, are there problems it poses artists and musicians?

4. What is the resultant experience for participants and audiences (or 'immersants') of an artistic AR experience?

This thesis approaches the above questions by making use of several established practice research methods. Broadly, these methods have led to practical contributions that will be explored in the following three study chapters:

- the creation and iterative design of multisensory sound ARt

- a set of open design patterns for creating similar sound ARt compositions and performances

These practical contributions have functioned both as ongoing research probes, and as platforms for open and reproducible artistic work for the wider experimental music research community. The methods present in this thesis have stayed consistent with their original proposal, with the exception of specific methods of data collection and analysis being adapted to suit the restrictions of the COVID-19 pandemic, which commenced three months after the start of research.

As will be developed on in Section 9.2, it is within this context of creating, developing, implementing and iterating on a set of open design patterns for AR art and music that the research methods employed in the following chapters are carried out. This started with a motivation for creating smaller experiences, that were simple in their sensory modulation and instrumental reactivity, with the view to later incorporate them into larger scale interactive AR experiences once sufficiently tested. However, due to COVID-19, the prospect of user-testing and iterating on the design of multiple experiences, especially large scale ones, through participant feedback became increasingly difficult to facilitate and plan for. Thus, I opted to focus on developing working sound art AR prototypes that I myself would compose with regularly, tweak, and iterate upon. Then, and there, an AR research and compositional practice began.

It is pertinent to mention that practical work, where carried out, has always been documented for analysis, open-research, and archival purposes. I found the combination of my personal website as well as GitHub and YouTube a suitable and cost-effective solution for this. Links to project files will be included in the study chapters, and cited websites have been archived using archive.today [1]. Before outlining the specific methods touched on in later chapters, I would first like to touch upon the concept of resistance, and its role in motivating the methodological approach taken in the thesis.

4.2 Resistance in Practice

Formative in the development of the methodological approach of this thesis has been the concept of 'resistance'. In short, this could be characterised as a motivation for changing or acting against the state of the art, practice, technology, or philosophy, out of a discontent for its status quo. This isn't to be confused by resistance in the sense of experiencing resistance to *do* something, although as might be expected, that has reared its head a few times over the

[1] https://en.wikipedia.org/wiki/Archive.today

last three years too. It is difficult to place resistance into the linear narrative of this text; some resistance formed my initial motivations for the carrying out of this research, and some was garnered along the way, especially around the time of the unfortunate uptake in 'Metaverse' as a term to describe the sum total of all creative XR development and labour. Either way, resistance has made up a large portion of my approach to AR technologies, its role within digital music and humanities more broadly. These forms of resistance can be separated into three main categories.

4.2.1 AR as Consumer Technology

As referred to in Section 3.2, contemporary design research in the fields of computational art and music have in recent years rallied behind the broader F/LOSS and OSH ethoses. This approach, often hand-in-hand with the Maker, DIY, and Hardware Hacking subcultures, stands in stark contrast to the goings-on of mega-corporations board rooms, with their design 'sprints', 'agile' workflows, and 'human (customer)-centred' design. The approaches taken by these subcultures towards embodied design and composition workflows however, has been highly beneficial for the field. In the case of digital music making, software, hardware, and live-coding tools like Pure Data (Pd) ↻, Maximilian, Supercollider, ixilang, Sonic Pi, TidalCycles, FluCoMa, and Bela have granted students, researchers, and composers across disciplines, free and beginner-friendly access to a wealth of software tutorials, examples, and tools for advanced real-time sampling and synthesis techniques.

It could be proposed, that this approach is motivated in part by a resistance against many of the 'features' typically found in commercial 'closed-source' software and hardware. Providing significant barriers to accessible learning, creativity, and artistic authenticity, these include lack of interoperability with other software, use of proprietary file formats, high initial or recurring subscription costs, and restricted access to lower-level parameters, functions, and settings. It is within this resistance against the closed-source and / or commercial that the practical work of this thesis attempts to situate itself, drawing on its implicit designerly practices and aesthetics. As a result, the path taken to address the key areas of the thesis has involved the bringing into the fore, knowledge from the creative practice of hacking, making, designing, and iterating with experimental and DIY open-source hardware and software.

While commentary on the considerable role of un(der)funded volunteer labour involved in open-source tools and projects is outside of the scope of this thesis, it is worth mentioning. In this way, 'open-source' is never taken to describe the best way of carrying out a project, rather I hope to convey that the ideals and features of an open-source ethic are beneficial to the aims of this thesis, vis-à-vis developing the understanding of new technologies within the new interface for musical expression (NIME) ↺ field, and attempting to manoeuvre what is essentially a minefield of technologies that are only available today because of U.S. defence funding.

4.2.2 AR as Visual

A second form of resistance that the methodological approach of this thesis explored is the ocularcentrism found in AR technologies mentioned previously in Section 2.4.1. As a practitioner of music, and audio related technologies, this has provided a significant portion of the motivation for carrying out the present research, as well as a significant portion of the challenges faced when attempting to develop AR as a medium for sound-based interactive experiences. Developing new interfaces for musical expression invariably leads to the appropriation of technology 'not meant' or 'not for' musical expression, and this is where NIME practice has considerable crossover into the maker / DIY / hardware-hacking subculture. The present thesis approaches ocularcentrism head-on, not through replacing the visual, but through re-ordering, with the aim to even-out, the sensory hierarchy of AR technologies.

Realistically, however, technologies relating to touch, and especially the chemical senses, present significant barriers compared to the visual and auditory senses in terms of access, cost, expertise, and time. In this research I have attempted to make room for future cases where this technology may be available, by using open-source hardware and software where possible, and by presenting a case for the design of MSAR experience in the set of design patterns in Section 9.2. Thus, the present thesis approaches audiovisual, gestural AR as a starting point for my own AR composition and performance, with a mindful eye (or ear) to the future capabilities of multisensory HCI technologies.

4.2.3 AR as Overlay

The third form of resistance drawn from in the thesis is that of AR's paradigmatic function as an 'overlay' device. So far, the origin of this approach, and contemporary alternatives to it have been explored Section 2.5, with a case being made by practitioners (Mann, 1994; Schraffenberger, 2018; Chevalier and Kiefer, 2020) towards re-situating AR as a process of perceptual mediation. In the present research, the resistance towards AR functioning as a HUD has led to propositions on how these approaches intersect with a 4EC approach to experience, later on, in Section 8.4.3. In practice, it has motivated the AR experiences developed in this research to go beyond passively layering sensory stimuli in front of immersants *as experience itself*. This is achieved by presenting experiences that are contingent on immersant movement, gesture, and environmental sounds, not only passive viewership. In this way, the AR experience can be thought more of as a hybridisation or alteration of reality rather than an simple HUD augmentation of reality.

As with multisensory technologies though, technologically achieved 'diminished reality' and other non-augmenting subforms are, in general, more computationally expensive and beyond the scope of the research practice due to lack of expertise and time. By way of acknowledging their importance as valid methods of perceptual mediation, they are accounted for in the design patterns presented in Section 9.2.

4.3 Research in Practice

The three ensuing chapters, *Composing area~ (2020)*, *Evaluating polaris~ (2021)*, and *Performing polygons~ (2022)* outline and analyse three AR interactive music systems developed over the course of this thesis, each with different but converging focuses. They make up practical contributions to knowledge, as well as forming the grounds for the propositions in Section 8.4. Though they were initially guided by a loose set of proto-design patterns (Bilbow, 2020*b*), it is through the insights and analysis gained in their creation and iteration that the Design Patterns for Sound ARt in Chapter 8 have been developed; they can therefore also be thought of as research probes in their own right.

area~ was the starting point for practical work in the present thesis. It is a non-visual AAR experience centred around the self-composition of a hybrid listening environment using an ambisonic microphone, head-, and hand-tracking. As will be expanded upon in the next chapter, due to the circumstances of the COVID-19 lockdown, I opted for an ABD method for the iteration and evaluation of the system. Out of the evaluation of this project, namely the endeavour to expand into A/V AR experiences, I discovered a suitable platform the develop the rest of doctoral research on: the open-source NS AR headset. *polaris~* describes an AR experience that was developed to examine the suitability of the NS AR headset's use in an A/V installation context. Participant studies were conducted and an evaluation of their experience was carried out via the grounded theory method of analysis. *polygons~* was a direct result of sharing the experience of artistic AR with the participants of *polaris~*. In proposing an Sound ARt Performance Practice, it describes the composition of a set of AR musical instruments, technical setup, and considerations of deploying an AR headset as a medium for musical performance.

4.4 Ethics Statement

The thesis research followed University of Sussex ethics guidelines approved by the Social Sciences & Arts Cross-Schools Research Ethics Committee, *polaris~* with the reference code: ER/SMB44/3.

4.4.1 Socio-economic Fairness

At all stages of this research, I have sought to minimise the outlay required to invest in technology needed to implement *polaris~*. This has meant opting for F/LOSS where possible: The software companion to the NS, Project Esky [2], Pd, and OBS. Ideally the 3D-engine used would also be F/LOSS, e.g. Godot, but due to time constraints I have opted for Unity which I am already experienced with, and which has great documentation and free learning materials.

Though the NS headset is OSH, I have not had time to develop a DIY OSH audio solution yet, but any bluetooth bone-conduction headphones are compatible.

Unfortunately, the *polaris~* experience (and as such, its framework outlined in Section 6.2) is not compatible with macOS, although it will be once Ultraleap provide their V5 drivers for hand-tracking on it.

It is worth noting that, as with most smaller suppliers of technology, the current global chip shortage has made getting hold of some components quite difficult at times, and recently the developers of the display driver board had to take the time to redesign it to get around this; the headset was not available to buy new for several months during this period. I suppose that this points to an issue: *'accessibility'* doesn't always correlate with *'availability'*, especially when trying to circumvent expensive consumer technologies.

Since beginning these studies, Intel has discontinued their T261/T265 range of products, meaning that anyone looking to build the headset today would have difficulty including movement tracking, a fairly essential component of effective AR experiences. I am fully aware of the roadblock this puts in the way of *polaris~* currently being reproducible as per its framework, but thankfully efforts are underway by developers in the community to solve this issue by migrating to Luxonis' modular and open-source range of tracking cameras; leaving the proprietary and closed-source hardware and software of Intel behind. If anything, their announcement has served as a reminder of the importance of FOSS/H components in community-led projects.

[2] 'Esky' is a colloquial term for an ice-cooler in Australia, etymologically deriving from the word 'Eskimo'. I acknowledge the use of this term as being pejorative towards the indigenous populations of the Greenlandic and Canadian Inuit, Alaskan Iñupiat, and Yupik peoples; fully recognise their human and land rights, and have made the effort to redact the word within the main body of this thesis.

A note on the environment

While it is certainly difficult to mitigate the environmental impact entirely from projects that rely on technology, I have opted for compostable PLA material for the construction of the headset used in the study to reduce e-waste in the event of breakage or updates to the hardware design.

4.4.2 Study Participants

Accessibility

In anticipating the possibility of a diverse set of accessibility needs, I provided stepped and step-free access instructions to get to the lab, maintained clearly formatted correspondence with participants via e-mail, and observed the university's COVID-19 policy during the study. Participants wearing glasses were able to use the headset with or without their glasses, and the volume of the AR scene was kept at a tolerable level, with the option given to participants to increase or decrease it.

Inclusion

Participants were recruited via internal University undergraduate and postgraduate mailing lists and were selected to ensure a diverse cohort of individuals from differing ethnicities, genders, and ages.

Remuneration

Study participants were compensated £15 each for the 45 minutes - 1 hour in which they took part in the study.

Consent

All participants provided written consent to take part in the questionnaire, experience, and interview; and also to being video and audio recorded during this time. They could at any time choose not to participate further, without being penalised or disadvantaged in any way. Their involvement in the study did not in any way impact their marks, assessments, or future studies. After analysis, their transcribed contributions were approved, and they had the opportunity to remove any anonymous, but still sensitive information.

Data and privacy

Data from the studies: video and audio recordings, transcriptions, and analysis files are secured on a separate hard drive and are password protected. All quotes and data have been anonymised in accordance with data protection legislation.

5 Composing area~

EXPLORING REAL AND VIRTUAL ENVIRONMENTS THROUGH GESTURAL AMBISONICS AND AUDIO AUGMENTED REALITY

Code:	https://www.github.com/sambilbow/area
Guide:	https://www.github.com/sambilbow/area/wiki
Publication:	https://dx.doi.org/10.21428/66f840a4.b74711a8
Archive:	Appendix A

5.1 Summary

In this chapter, I outline the development and evaluation of the *area~* system that I created in 2019 as the initial research probe into sound-driven AR experiences. *area~* enables its user to record, manipulate, and spatialise virtual audio samples or nodes around their immediate environment. Through a combination of ambisonics audio rendering and hand articulation tracking, this system calls attention to the ability of non-visual AR, here, AAR, to provide new aesthetic experiences of real and virtual environments. Through an ABD study, these experiences are discussed in relation to the research question: *'How can we better understand relationships between virtual and real environments through gesture and virtually placed AAR objects?'*. The system is contextualised within the move in computational art, and indeed, broader HCI research, towards multisensory interaction. In particular, *area~* is situated in the creative practice of works using MSAR as a medium to create expressive computational sound art.

The *area~* system is a gestural sound sampler that uses hand and head tracking to place and manipulate virtual audio sources in the user's environment, heard through bone conduction headphones which transmit sound directly to the cochlear without occluding the their hearing. This allows the them to experience *virtual audio environments* overlaid seamlessly onto the *real audio environment*. Through gesture, they can interact with and shape the combined *real and virtual audio environment* surrounding them.

The three technologies used in *area~* are gestural hand tracking, rotational head tracking, and ambisonics. The gestural hand tracker used in the system is a Leap Motion LM-010 Controller [1], a USB infrared camera device that provides location and orientation data output of individual finger joints (and therefore hands) when they are presented above the device. The Leap Motion controller (LMC) ⥀ has been adopted in a multitude of settings such as being mounted on VR headsets [2], and converting hand gestures to musical instrument digital interface (MIDI) ⥀ [3]. More recently, Ultraleap are investigating the use of this same technology with gesture-based public information screens to help combat the 'hygiene risks of touch screens' (2020).

Rotational (not positional) head tracking is achieved via an inertial measurement unit inertial measurement unit (IMU) ⥀. This small and inexpensive component provides orientational data output at 20 times a second. When affixed to the head via a headset or headphones, it is a relatively easy and cheap way of implementing head tracking into the system.

Ambisonics is an audio format that allows for full-spherical audio capture and playback

[1] https://www.ultraleap.com/product/leap-motion-controller/
[2] https://archive.vn/GQtAH
[3] https://archive.vn/3M1PX

(Gerzon, 1973), meaning that it includes sound sources above and below the listener as well as the conventional horizontal plane. There are four recorded channels (referred to as A-Format) that, unlike regular mono, stereo or surround sound formats, contain no information about the speakers that the signal should be delivered to. Rather, these channels can be encoded in such a way as to describe a three-dimensional field of sound referred to as B-Format, allowing the producer or artist to think in terms of sound sources in three dimensions rather than conventional speaker placement. B-Format can be decoded through ‘virtual microphones’, any number of which can be placed within this three-dimensional sound field to provide standard channel outputs.

For example, in *area~*, I have used a RØDE Soundfield NTSF-1 microphone array comprised of 4 microphones. The A-Format output is encoded to B-Format by an audio plugin. A software library decodes the B-Format to two responsive, binaural, virtual audio output channels. This all occurs in real-time, so that the microphones inside the three-dimensional sound field rotate proportionally as the composer moves their head, providing realistic changes to what is heard.

5.2 Designing *area~*

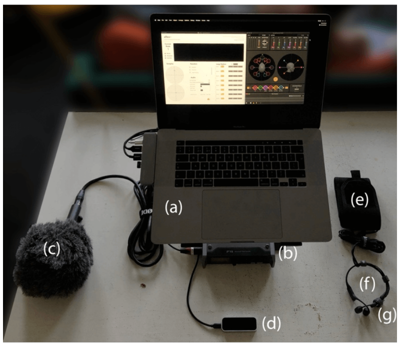
The *area~* system, which stands loosely for ‘augmented reality environmental audio’ aims to afford its user the ability to spectromorphologically (defined by Smalley to concern spatial, temporal and textural qualities of sound (1997)) manipulate sounds from their environment into a *virtual audio environment*. Through bone conduction headphones and head tracking, this sound field is heard in synchronicity with their actual environment. The system was created in order to explore and reveal the relationship between real and virtual environments in AAR systems.

5.2.1 Hardware Implementation

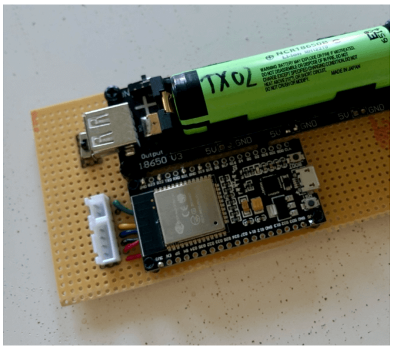
The on-desk hardware for the *area~* system shown in Figure 2 includes (a) a laptop running the Max MSP [4] patch, (b) a 4 channel input audio interface, (c) an Ambisonic microphone, and (d) a Leap Motion Controller.

The wearable hardware used for the *area~* system comprises 2 sections: (e) a belt pouch containing a printed circuit board (PCB) ⟳-mounted ESP32 microcontroller [5] and 18650 battery (shown in Figure 5.2), and (f) a pair of bone conduction headphones [6], with (g) an IMU for

[4] https://cycling74.com/products/max
[5] https://www.espressif.com/en/products/socs/esp32/overview
[6] https://aftershokz.co.uk/products/aeropex



(a)



(b)

Figure 5.2: *area~* hardware and PCB

tracking head orientation.

The IMU and ESP32 are connected via a detachable 1.5m heat shrunk cable that runs from the back of the bone conduction headphones, down the length of the user's back and into the belt-mounted transmitter pouch. With the integration of an Arduino library [7], the IMU data is transmitted to the laptop via Bluetooth from the ESP32. Audio is transmitted to the headphones via Bluetooth from the Max MSP patch running on the laptop.

The only hardware that needs to be accessible for the person composing with *area~* is the LMC and the wearable hardware system. The laptop and audio interface are ideally hidden from view so as to minimise distraction. The microphone should be placed in a location that will provide them with access to sounds that they wish to compose with.

5.2.2 Software Implementation

The patch (Figure 5.3) uses the audio plugin [8] shown in Figure 5.4 to encode the A-Format ambisonics microphone input into B-Format (a three-dimensional sound field), or what I will refer to as the *ambisonic palette*. This *ambisonic palette* is not heard by the composer; instead, they can sculpt from it, forming their own audible *(B-Format) virtual audio environment* through hand gestures. I have defined these gestures in Max MSP with help from the Institute for Research and Coordination in Acoustics Music (IRCAM) Leap Motion library (2014) [9], and they occur over three stages of interaction: ***record, manipulate, spatialise***.

Record

The **recording or 'sampling' stage** is initiated by making a left-hand grab above the LMC, the longer lasting the grab, the longer the portion of audio from the *ambisonic palette* is sampled.

[7] https://github.com/kriswiner/ESP32/
[8] https://www.rode.com/soundfieldplugin
[9] https://github.com/JulesFrancoise/leapmotion-for-max

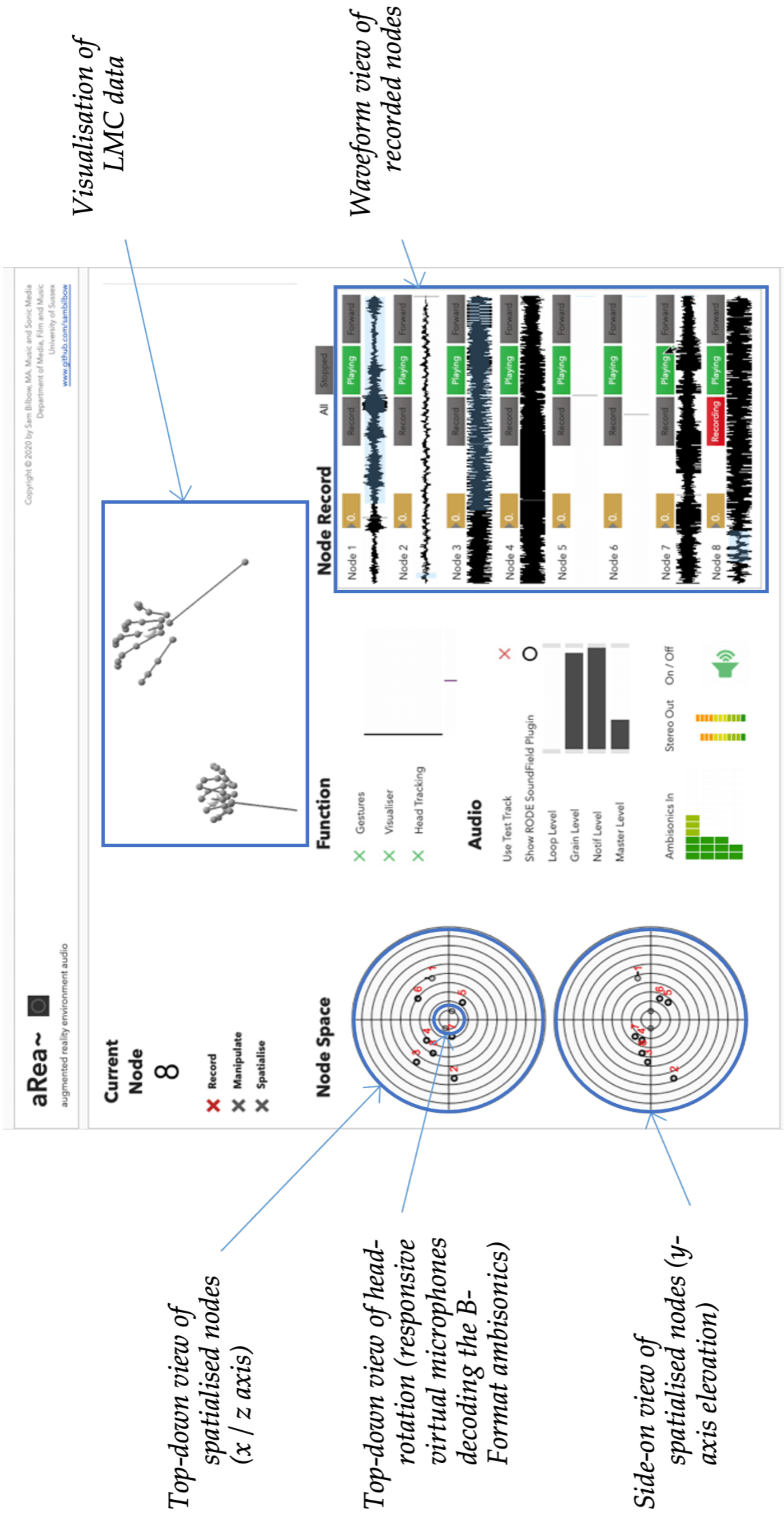


Figure 5.3: *area~* Max MSP patch (code)

Figure 5.4: RØDE Soundfield Plugin

Parameter	Mapping	Explanation
Centre Frequency	• **Point between both hands (x-axis)** • Linear map **from** LMC x-axis sensor range **to** BPF frequency (0 - 20kHz)	Central frequency value (Hz) of filter.
Filter Strength	• **Absolute inter-hand distance (x-axis)** • Linear map **from** LMC x-axis sensor range **to** BPF Q value.	Widen / narrow frequency range of filter
Gain	• **Average hand height (y-axis)** • Exponential map **from** LMC y-axis sensor range **to** 0.5 - 1.5x BPF gain	Increase / decrease the volume of the filter

Table 5.1: area~ Max MSP patch band-pass filter parameter mappings for hand positions

The three-dimensional coordinates of the hand above the LMC correlates with the location of audio recorded (this is achieved by mapping the hand coordinates to a virtual microphone inside the *ambisonic palette*), essentially allowing the composer to record sounds around their person in three dimensions. Upon letting go of the grab gesture, the sample plays on repeat (using the karma~ Library [10]) through the bone conduction headphones, thus setting up the session's *virtual audio environment.*

Manipulate

The manipulation stage is automatically initiated after the ending of the previous grab gesture and uses translational (x, y, z) and rotational (roll, pitch) values from both hands when above the LMC. There are two audio effects being manipulated, with parameters from these effects mapped in different ways to the translation and rotation of the composer's hands.

- The first effect is a band-pass filter (BPF) ⟳ which accentuates certain audio frequencies of the sample. The frequency, strength, and gain of the filter is determined by the parameter mappings detailed in Table 5.1

- The second effect is a semi-random granular synthesiser. This selects and copies a section of the sample and deconstructs it into several hundred grains. The section of the sample granulised, and the individual grain duration is determined by the parameter mappings detailed in Table 5.2

When the composer decides to end manipulating the sample, they can do so by performing a grab with both hands. Once this happens, the BPF and granular synthesis parameters are frozen for that sample.

[10] https://cycling74.com/tools/karma-samplerlooper-external

Parameter	Mapping	Explanation
Granulised sample section starting position	• **Right hand roll** • Linear map **from** LMC right hand roll sensor range (scaled 0 – 1) **to** 0 – 100% position on sample	Where in this sample should I start the granulation?
Granulised sample section ending position	• **Right hand pitch** • Quadratic map **from** LMC right hand pitch sensor range (scaled 1 – 0 – 1) **to** 0 – 100% position on sample	Where in this sample should I end the granulation?
Randomised grain duration lower bound	• **Left hand roll** • Linear map **from** LMC left hand roll sensor range (scaled 0 – 1) **to** grain duration lower bound (0ms – entire sample section length)	Lower bound for randomised grain duration.
Randomised grain duration upper bound	• **Left hand pitch** • Quadratic map **from** LMC left hand pitch sensor range (scaled 1 – 0 – 1) **to** grain duration upper bound (0ms – entire sample section length)	Upper bound for the randomised grain duration.

Table 5.2: area~ Max MSP patch granular synthesiser parameter mappings for hand rotations

Spatialise

The spatialise stage begins once the manipulation stage has ended. The three-dimensional space above the LMC is mapped to the *virtual audio environment*, in which the composer is currently listening to the sample that they have recorded. The composer can use their right hand to move the sample around the *virtual audio environment*. For an example of the effect this has, moving the hand between the two extremes of the x-axis (left to right) results in hearing the sample move from ear to ear. The spatialise stage is ended by grabbing with the right hand.

Once the spatialise stage has ended, the composer has the option to repeat the process 7 more times, allowing for the creation of a *virtual audio environment* comprised of up to 8 spatialised audio samples, or what I refer to as *nodes*.

Summary

The audio signal arriving in the two conduction pads in the headphones are the signals of two equidistantly spaced virtual microphones inside the *B-Format virtual audio environment* that decode it into two channels, left and right. Further interaction comes from composer head movement which, at all times, is mapped to the revolution of these two virtual microphones around the central point of the *virtual audio environment*. This means if there is a node playing to the left of the composer, rotating the head 90° anticlockwise results in the *node* now sounding as if it is in front of the composer's face. This is achieved via the Institute for Computer Music and Sound Technology (ICST) Ambisonics Library (Schacher and Kocher, 2006) [11] and is elaborated

[11] https://www.zhdk.ch/forschung/icst/software-downloads-5379/downloads-ambisonics-externals-for-maxmsp-5381

on in the sections Section 5.3.3 and Section 5.4, but for now it is worth mentioning that it allows for immersion into a combined *real and virtual audio environment*.

To summarise, the patch can be categorised into having two inputs: audio from the composer's environment and hand gesture, and one output: *the virtual audio environment*. In the background, this audio input is decoded into the *ambisonic palette* (inaudible), which is acted on by the composer's hands to form one audible output: the *virtual audio environment*, which is comprised of up to 8 *nodes*. Through the choice of sensory overlay (bone conduction) and integration of head tracking, this *virtual audio environment* is experienced synchronously with the composers' real, multisensory environment.

5.3 Composing with *area~*

5.3.1 Autobiographical Design

Originally, the study was planned for late March and would involve several participatory interaction studies. However, due to the UK lockdown in response to the unfolding COVID-19 pandemic, this was postponed until later in the year. Instead, I investigated the system using an ABD method, framing it as a hypothesis study to better understand relationships between virtual and real environments, in the hope of developing a practice-led method for creating and researching MSAR experiences.

Autobiographical design is defined as 'design research drawing on extensive, genuine usage by those creating or building the system' (Neustaedter and Sengers, 2012). Neustaedter and Sengers define 'genuine usage' here to mean that changes are 'based on the true needs of the researchers, rather than them pretending to have needs expected of target users'.

Due to the lockdown, and therefore inability to conduct in-person user-tests, this research method was beneficial as I was spending large amounts of time with the system. Moreover, there are several suggested requirements of employing this research method that Neustaedter and Sengers highlight that are true of the *area~* system:

- The existence of a genuine usage of the system
- The system being already developed
- The ability for fast tinkering
- Record-keeping of the design process
- Long-term usage of the system

Furthermore, as AR technology moves towards being a component of future general personal computing, there is a need for first-person research methods that take into consideration the effects of prolonged system usage as well as the arising relationship between participant and system (Desjardins and Ball, 2018). Moreover, these methods have been found to be specifically relevant to wearable systems (Cecchinato et al., 2017).

A disadvantage of using ABD as a research method is its inability to establish generalisability (also the case with ethnography, case studies and participatory workshops), which is why I opted for participant studies in the evaluation of *polaris~* in Chapter 6.

5.3.2 Design

The study was designed as a cycle, in order to promote fast tinkering, record-keeping, and long-term usage in line with ABD guidelines.

1. Over three sessions, ideally during the same week, the system is used with a logbook at hand in order to facilitate record-keeping of hardware setup, *node* manipulation and completed *real and virtual audio environment* listening experience remarks.

2. After each session, the notes are formalised into a database and categorised as 'composer experience remarks' or 'improvement remarks'.

3. At the end of the week, the three sessions' notes are summarised into a 'check-in' document, where composer experience remarks are collated, and improvement remarks are further categorised into lists pertaining to the area of the system that needs improvement or change.

4. Those changes are then made to the system and the cycle restarts.

5.3.3 Results

Hardware Location

I have observed that an environment with a lower noise floor is desirable and have implemented a normaliser to deal with re-recording loud background / ambient noises during successive *node* recording. I found myself basing the choice of microphone placement on what I wanted the *virtual audio environment* to sound like. Since the system uses an ambisonic microphone, consideration of the spherical 360° field of the microphone would lead to a richer *ambisonic palette* and subsequent *virtual audio environment*.

Two sessions were based outdoors and involved natural sounds such as birds, trees and wind, as well as passing cars. One of the sessions was inside and took place at the same time my partner was on a Zoom call, and therefore the *ambisonic palette* was invariably based on her speech and my movement and action inside the room. I want to look into placing the microphone inside bushes, trees, etc. rather than in open spaces to explore aesthetically the *virtual audio environment* that arises from such placement. Furthermore, the relationship between *real and virtual audio environment* would be quite different. Through their ears, the composer would be rooted in their position in the environment, but because of the inherent blend between hearing and bone conduction, they would simultaneously experience the sonic environment of the bush mediated by the Max MSP patch.

Experiences

The system takes considerable time to set up, especially when documenting with video, audio, and notes. This process could certainly be streamlined further. Overall, I was pleased with the sound quality; the microphone picks up the environment very clearly. However, I remarked that the manipulation stage could feature more interesting real-time auditory effects on the *nodes*. The blending of *real and virtual audio environment* is achieved well via the bone conduction headphones and there was a subconscious registration via the head-tracking that gave me the very real impression that there was a 3D environment of *nodes* around my body.

The IMU on the bone conduction headphones sometimes provides erratic and erroneous data, leading to accidental revolutions of the *virtual audio environment* around the head. Despite technical difficulties such as this, in one ABD session, when I took the headphones off, I wrote that ‘I felt like I’d been disconnected from something’ and that ‘my senses felt heightened before I took them off, not only to the *virtual audio environment*, but now more sensitive to the audio content of my real environment.

If I managed to capture an infrequent environment sound, such as a particular bird call, or a sentence of spoken word, the fact that the patch is set up to loop the samples gave a certain permanence to that otherwise impermanent sound. On multiple occasions I could not tell if the sounds of birds I was hearing originated from a *node* or from within a tree.

Arising Interactions

The maximum sample length is currently 28 seconds, but I have found myself mainly sticking to shorter loops, creating quite repetitive and rhythmic sequences. I remarked that grains from the synthesiser sounded like a permanent record of my gestures’ effect on the environment. I liked the playfulness of being able to record a sound from a certain location in my *real audio environment* and place it in different location in my *virtual audio environment.*

Despite the wearable hardware being wireless, hand interaction with the *area~* system is inherently limited to being in range of the LMC (often placed on a table). I found myself wanting to be able to move around my environment whilst being able to record new nodes and hear existing nodes move relative to my body position.

5.4 Evaluating *area~*

Overall, the results from my ABD method have shown that *area~* is an effective tool for examining the combinatorial relationship between real and virtual environments. Despite the system's hardware setup requiring some further work to allow for quicker start up and more accurate head tracking, it has provided me with novel aesthetic experience through:

- The blending of *real and virtual auditory environments* to create a third, augmented environment that was greater in experiential nature than the sum of its parts (not simply a combinatorial layering)
- The ability to spectromorphologically manipulate sounds in real-time in this third environment with the body
- The potential for creating believable illusions of real-world sound sources from these manipulated and spatialised virtual sounds.

The tables of parameter mappings shown in Section 5.2.2 may seem like a chaotic mess, however, time has been spent making these mappings intuitive. For example, the representation of volume to a vertical scale corresponds with findings that non-musicians are relatively competent at attributing the size of air-gestures to heightened musical dynamics (Godøy et al., 2006; Caramiaux et al., 2010). As for the BPF's horizontal pitch mappings, this is mainly based on the visual representation of frequencies on a horizontal scale often found in the user interface of such filters. Nevertheless, it is pertinent to mention that field of psycho-musicology research (Timmers and Li, 2016) finds a correlation between pitch representation and horizontal space i.e. lower pitch to the left, higher pitch to the right. Although this is often attributed to the internalised representation of horizontal pitch on pianos by keyboard-playing musicians (Lidji et al., 2007; Rusconi et al., 2006), it has been found that this effect also propagates in non-musicians (Weis et al., 2016). This is also found to be the case in the 'Playing air-instruments' study carried out by Godøy, Haga, and Jensenius (2006).

Figure 5.5: *area~* 360° video and ambisonic documentation (from Bilbow, 2020*a*)

In contrast, interaction with the granular synthesiser is not made to be intuitive; instead, I have opted to hide or black-box the interaction through a mix of linear and quadratic mappings on each hand. This is in order to stir curiosity in the composer and induce play, as I found in Section 5.3.3: 'I remarked that grains from the synthesiser sounded like a record of my gestures' effect on the environment'.

Indeed, whilst outlining the material epistemologies of DMI, (Magnusson, 2009*b*) describes black-boxed DMIs as containing 'knowledge of its inventors, which means that the users of the instrument do not need to have a deep knowledge of its internal functions', furthermore clarifying that there is a 'continued oscillation between a mode of conceptual (system design) engagement with the instrument and [an] embodied (performative) relationship with it'. This 'oscillation' displays, in turn, an underlying synergy between DMI development and the ABD process, perhaps due to the similarities in requirements of the processes outlined in Section 5.3.1. This synergy has led to the use of ABD in the development of many DMIs and interactive music systems (Kiefer et al., 2020; Martin, 2017; Turchet, 2018; Unander-Scharin et al., 2014).

As a system for creating computational sound ARt in the form of in-situ AAR experiences, *area~*'s artistic output is firstly a real-time compositional experience. In order to document these experiences of the system however, I have included the automated recording and saving of both the *ambisonic palette* (the ambisonic recording of the real audio environment), and the users *virtual audio environment* as separate B-Format .wav files in the project directory. These separate B-Format .wav files could be merged and decoded from B-Format to any number of speakers for a multi-channel installation of field recordings or manipulations of environments made with *area~*. This also leaves open the potential for *area~* to be used as a compositional tool for interactive soundscape composition.

I also chose to merge and decode a set of these recordings to binaural stereo format, and have time-synced this recording with a 360° video and a screen recording of the patch that was taken during the system's use. This allows my composition of the *virtual audio environment* to be experienced second-hand with headphones. Dragging the screen in different directions with mouse/touchscreen emulates hearing the difference in environment if I moved my head in those directions. Optionally, an inexpensive smartphone VR headset (£5 - £15) can be used to heighten the interactivity of the experience. A screenshot of the 360° video (Bilbow, 2020*b*) is shown in Figure 5.5. The potential for users' experiments with *area~* to be captured and re-experienced interactively could have interesting applications, effectively allowing users to explore each others' lived aural experience of the system.

6 Evaluating polaris~

An Audiovisual Augmented Reality Experience Build on Open-Source Hardware and Software

Blog:	https://www.sambilbow.com/projects/polaris
Code:	https://www.github.com/sambilbow/polaris
Guide:	https://www.github.com/sambilbow/polaris/wiki
Publication:	https://dx.doi.org/10.21428/92fbeb44.8abb9ce6
Archive:	Appendix B

6.1 Summary

This chapter outlines the development and evaluation of the *polaris~* experience. *polaris~* is built using a set of open-source hardware and software components that can be used to create privacy-respecting and cost-effective A/V AR experiences. Its wearable component is comprised of the open-source NS AR headset and a pair of bone conduction headphones, providing simultaneous real and virtual visual and auditory elements. These elements are spatially aligned using Unity and Pd to the real space that they appear in and can be gesturally interacted with in a way that fosters artistic and musical expression. In order to evaluate the *polaris~*, 10 participants were recruited, who spent approximately 30 minutes each in the AR scene and were interviewed about their experience. Using grounded theory, the author extracted coded remarks from the transcriptions of these studies, that were then sorted into the categories of Sentiment, Learning, Adoption, Expression, and Immersion. In evaluating *polaris~* it was found that the experience engaged participants fruitfully, with many noting their ability to express themselves audiovisually in creative ways.

The objective of this chapter is to evaluate *polaris~* as an AR experience for its ability to provide a space for gestural A/V expression, primarily through a user study, and later using the grounded theory method to extract relevant themes from participant interactions. The outcome of this research has contributed thoroughly to the design patterns in Section 9.2.

6.2 Designing *polaris~*

The *polaris~* experience itself is built using mostly open-source hardware and software. As well as creating the experience, I was interested in keeping a log of its framework in order to ensure its reproducibility and to facilitate further creation of a wide variety of A/V AR experiences. Any 'artist-developer' [1] wanting to work on similar experiences should have the ability, when following this framework, to rapidly create and prototype low-cost and privacy-respecting sound ARt experiences, and instruments..

6.2.1 *polaris~* Hardware

Project North Star

The primary section of wearable hardware is the NS AR headset, as open-sourced by LeapMotion (now Ultraleap) in 2018. It has a 3D-printable assembly, and its circuit boards, cables, and

[1] By using the term artist-developer, I refer to the media artist, creative coder, digital musician, or indeed any of the other many terms used to describe the category of artist who uses code and/or technology as their medium of artistic expression.

(a) Playing a virtual piano

(b) Resizing and moving virtual objects

Figure 6.2: Project North Star in use during the prototyping phase of *polaris~*

screens are available to buy online; my NS cost about £500 in total to build - 5 to 6 times less expensive than the commercial AR headsets mentioned, while maintaining industry-leading hand-tracking and 6DoF tracking.

However, the time needed to build one and understand its workings well enough to troubleshoot any issues one faces may be a barrier to entry [2]. Additionally, the finish material is not as polished as commercial headsets, and the overall size is larger and clunkier. It also needs to be tethered by USB and DisplayPort cable to a host computer or mobile compute pack.

Despite these drawbacks, my own experience of the headset has led to the rapid creation of many A/V AR prototypes. The fact that it requires no account to use, no developer's license to work with, and no data to be sent away to corporate servers has only added to my comfortability of using it as a creative tool.

Figure 6.3: Project North Star worn with the addition of bone-conduction headphones

Bone Conduction

The secondary piece of hardware in the system is a pair of bone-conduction headphones, seen in Figure 6.3. These have been used as a method of auditory display in several other AR projects (Lindeman et al., 2008; Barde et al., 2016; Chevalier and Kiefer, 2018), typically for their ability to deliver audio in an unobtrusive fashion, as well as their comfortability and cleanliness in installation settings. They do not obscure the wearer's hearing of their real environment, making them suitable for emphasising the intertwined nature of virtual and real components of an AR

[2] I have found it a surprisingly integral part of the way I make sense of my creative practice, and fortunately there is a NS Discord server with over 2400 helpful members that I have relied on heavily!

experience.

6.2.2 *polaris~* Software

Unity

polaris~ uses an open-source software companion to the NS headset developed and maintained by Damien Rompapas (2020). At run-time, this Unity plugin (also making use of Ultraleap's Hands plugin) computes sensor readings from both the hand- and movement-tracking sensors and recreates the hand and headset pose in real-time inside the Unity scene. With the pose computed, it outputs the resultant view to the displays of the headset, rendering anything in the Unity scene relative to it.

Thanks to Unity's in-built audio spatialisation, any audio sample attached to an object in the Unity scene is, by default, spatialised in 3D and output via the bone-conduction headphones.

Pure Data

In my own research, the desire to implement more than just sample-based audio interactions led me to experiment with many different options for implementing real-time audio synthesis. I ranked each option I found by its ability to fulfil the below criteria: (a write-up can be found on my website, or see Section B.2)

1. Uses Unity's in-built audio spatialisation.

2. Low computational cost on the host computer, and ability to be instantiated tens to hundreds of times procedurally.

3. Ability to afford the artist-developer a wide palette of synthesis techniques.

4. Allowing real-time parameter control of sounds via movement, gesture, and interaction with GameObjects in the Unity scene.

5. Ability to rapidly prototype sound synthesis techniques and sonic interactions.

6. Being free, open-source, and cross-platform.

Meeting all these requirements was the LibPdIntegration project developed and maintained by Niall Moody and Yann Seznec. It allows for the use of Pd patches in Unity, which, at run-time, are compiled to libPd (an embeddable version of Pd), and whose output is fed in real-time to the sound output of the GameObjects they are attached to [3].

To summarise, the use of the NS companion software in conjunction with LibPdIntegration, allows for the creation of objects in an AR scene that can have their own Pd patches. These can be parametrised to gesture, movement, and interaction, in ways that manipulate their audio synthesis in real-time and at low computational cost. This all while existing three-dimensionally in the participants' visual and auditory fields. The fact that this is delivered via an optical-see through headset and bone-conduction headphones results in an experience that does not significantly hinder (compared to VR) the participants' ability to see and hear their real environment - augmenting and hybridising reality rather than replacing it.

6.3 Participant Studies

In 2021, I ran a participant experience study of *polaris~*, the first experience I created with the above framework. The main objective of the study was to extract (via grounded theory) participant sentiment towards their ability to audiovisually express themselves through gesture and movement in the AR experience. Participants were recruited via university mailing-list, and were a mix of undergraduate and postgraduate Media, Film, and Music students.

6.3.1 Questionnaire

Participants completed a questionnaire, in which I asked for their age, gender identity, ethnicity, and occupation, to ensure a diverse and inclusive variety of participants. The mean age was ~24.7 years old, with a range between 19 and 37; there were 6 female and 4 male participants, belonging to a diverse group of ethnicities.

6.3.2 Tutorial

The participants were inducted into the experience via an introductory five-minute tutorial, the purpose being to ensure safety, build trust, and allow space for questions before beginning. This took the form of a narrated slideshow, in which I outlined the devices and interactions they should expect in the experience.

[3] The inclusion of Pd means that the many artist-developers can rely on a program that has existed in the field for nearly 25 years, many of whom will have experience using it.

6.3.3 The *polaris~* Experience

Once the participant was wearing the headset and headphones, confirmed they were comfortable and they were standing in the starting position [4], I began the Unity scene (a full demonstration of the scene can be found on my YouTube channel), and let them know that the experience was about to start.

The experience involved nine floating iridescent 'orbs', scattered at different distances from the starting position. The orbs would individually emit a repeating tone, whose pitch and tempo varied from orb to orb. Upon emitting a sound, the orb would eject a shower of white particles.

Figure 6.4: Through-lens footage of the floating orbs in the polaris~ AR scene (from Bilbow, 2022*b*, at 00:19) (code)

Participants were invited to explore the space at their own pace. They could, of course, view the orbs from different angles, and hear their tones get louder and quieter as well as panning from ear to ear as they walked around them. I then prompted them to direct their gaze towards their hands, which were outlined, and when turning the left hand to face them, a menu appeared to the right of their palm. The menu contained two buttons, one labelled 'Change Hand Colour', the other 'Toggle Interactions'. I prompted them to tap the top button, which upon depressing slightly and providing an auditory 'click', changed the colour of their hand's outline.

Figure 6.5: Through-lens footage of the hand outline, menu, and button activation in the polaris~ AR scene (from Bilbow, 2022*b*, at 2:20)

Upon toggling the second button on, constant streams of particles started emitting from the centre of their palms. These particles persisted for approximately five seconds to conserve computational power. While the button was toggled on, and the streams were emitting, each hand also produced a continuous noise (code).

[4] As the headset was tethered to a computer, keeping the starting position the same between participants meant that the position of virtual content could be approximated to a clear space in the lab, marked by tape on the floor

In addition to these interactions, a total of five further interactions existed in the experience. The first two concerned the position, orientation, and gesture of the hands, relative to the participant. Firstly, they could modulate the depth of a vibrato effect on the sound of the particle stream by gradually turning their palms towards their face. Secondly, they could affect the sound's low-pass filter (LPF) cut-off frequency by pinching their fingers together into a point, resulting in a hissing sound; paired with the visual feedback of narrowing the particle stream.

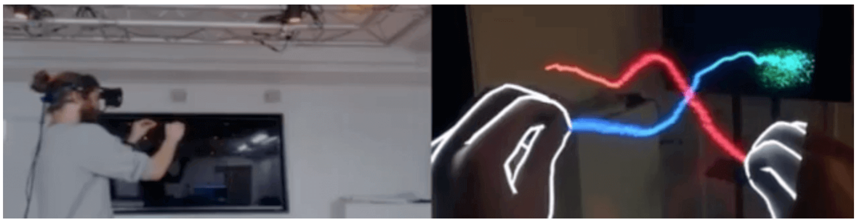


Figure 6.6: Through-lens footage of the pinch gesture's effect on the particle streams in the polaris~ AR scene (from Bilbow, 2022*b*, at 7:56)

On pointing their palms in the direction of an orb, the particles would gravitate towards the orb, and begin to slow down, orbit, and rotate it. Depending on which palm was pointing towards the orb, there would be an additional effect that increased in intensity as the participant persisted in pointing towards the orb. When pointing their left palm, over the course of 20 seconds, the orb's tone and white particle burst increased in tempo. When pointing their right palm towards an orb, over the course of 5 seconds, the depth of a tremolo effect on that orb's tone increased, with the paths of the white particles emitted from the orb becoming more erratic and corkscrew-like.

Figure 6.7: Through-lens footage of the orb's gravitational effect on the hand particles in the polaris~ AR scene (from Bilbow, 2022*b*, at 8:14)

Exploration of the scene differed between participants, but once they had either found or been shown the interaction methods in the scene and had either explored their variety or asked if there was anything else that they could do, I would ask them to try some experimental interactions.

Taking advantage of the vast number of parameters available to edit in Unity, I then changed elements of the visual experience [5] in real-time, asking for participant feedback on elements

[5] Since the 11 Pd patches (9 for the orbs, and 1 each for the hands) were compiled at run-time they could not be edited on the fly

they preferred, and why. These elements of visual experience involved the orbs size, shape, gravity strength, and range; particle size, speed, lifetime, and colour.

Figure 6.8: Artificial composite 3rd and 1st person views of a polaris~ participant drawing in mid air during the experimental section, note the scene gravity being turned on. (from Bilbow, 2022*a*, at 0:00)

6.3.4 Interview

The next step of the study was a 10-minute interview, in which I asked participants about the positive and negative aspects of the experience, and anything they could suggest that would improve the experience. Questions were left deliberately broad due to the use of grounded theory to draw out themes for later analysis. I used a topic guide (see Appendix 1) to keep follow-on questions for replies related to the experience. This was in the form of a set of questions from the validated questionnaire titled 'User Experience in Immersive Virtual Environments' by Katy Tcha-Tokey et al. (2016), which I adapted to suit AR.

6.4 Results

6.4.1 Grounded Theory

I chose the constructivist strand of grounded theory as developed by Kathy Charmaz (2006) (building on the initial work by Glaser and Strauss (1967)) for my method of data analysis due to its ability to build theories from gathered data. Generally, generating a grounded theory extracts relevance from 'codes' - line-by-line summaries of transcribed speech, that are then iteratively

Figure 6.9: 5 categories, 37 subcategories and ~700 codes visualised in NVivo.

and repeatedly refined, and sorted into categories. This contrasts approaching data collection with a specific hypothesis in mind.

In the constructivist version of the Grounded Theory method, rather than assuming emergence of 'unproblematic' and 'objective' categories from the data itself, categories are admitted to being 'mutually constructed' through interaction by the researcher with the data, considering and highlighting both the position and subjectivity of the researcher, as well as the partiality, and situational nature of the data itself.

In this instance, a study where I set out to evaluate the experience of participants in an A/V AR scene, I believed that it was suited to provide a rich set of data from which to critique and iterate the experience, and eventually build a set of MSAR design guidelines.

Transcribing the nearly 7 hours of experiences and interviews, lead to 45,858 words, and approximately ~700 individual codes in the qualitative research software NVivo. These were sorted into 37 subcategories, with a total of 5 categories.

6.4.2 Sentiment

Included in this category are emotions elicited by the experience, the majority of which were related to novelty. Participants felt a mixture of emotions, most frequently wonder or awe at the

(a) 'The Force' (from Kershner, 1980)

(b) Mid-Air Displays (from Spielberg, 2002)

(c) Psychedelic Visuals (from Noé, 2009)

Figure 6.10: Participants likened the experience of *polaris~* to 'being in' *Star Wars* (a), *Minority Report* (b), and *Enter the Void* (c)

visual components of the scene, and enjoyment of the scene components and the interactions with them.

One participant felt fixated by the experience: *'I am quite obsessed by this button'* (P9), whilst another felt satisfaction: *'Like a fascination, wonder, it was quite satisfying as well'* (P3).

All participants made ample use of simile and metaphor, likening visual elements to liquid, snow, fire, fireworks, magic, and confetti. The sound design was said to be *'ocean-like'* (P7) or *'wind-like'* (P1), and participants expressed similarities in their experience to 'being in' movies such as *Star Wars, Minority Report, and Enter the Void* - Figure 6.10.

6.4.3 Learning

From this category of codes, is clear that the experience involved an element of learning different functions and abilities. One participant remarked: *'I was unsure, and I didn't know what would lead to a change in what I did, but after a point I understood'* (P6). Another linked learning as resulting in immersion: *'Each step that you learn something new about what you can do in that environment, that's when you become more and more immersed'* (P9).

6.4.4 Adoption

This category includes codes that referred to issues that could be a barrier to using the technology, recommendations for different utilisations of A/V AR, and codes relating to safety and accessibility implications of adopting AR.

Comfort and Fit

8 out of 10 participants struggled with the fit of the headgear on the NS headset not being tight enough. As a result, some participants had to hold the headset with one hand throughout the experience. One participant expressed that this *'stood as a hurdle to [the] experience'* (P1),

and another specified how this affected their involvement with experience in more detail: *'[Discomfort] doesn't ruin it, but it definitely brings me back to reality really quickly'* (P10).

Alignment and Tracking

Related to the above, were codes that referred to issues with alignment of content onto the real environment, such as the floating orbs and the outline of the hands. These were a product of the sensors, lighting, and content of the lab space. One participant even described the slight delay and misalignment of the hand outline as *'trippy'* , going on to say that they *'sort of like that it's a bit out'* (P1).

Uses of AR and comparisons to other media

A wide variety of possible uses of A/V AR were highlighted by participants, including communication, conveying certain messages by highlighting important subject matter, art and music, virtual worlds, and video games. One participant, who studies Media for Development and Social Change and works with environmental non-governmental organisations NGOs, remarked that using A/V AR could help generate more interest in environmental conservation, because experiencing AR made them feel *'for some reason I act like this [virtual content] is more real than it is'*, going on to say that *'rather than just watching it on the screen, you'd be more integrated'* (P6).

Another participant, studying on the same course, considered the use of AR in the documentation of the lived experiences of vulnerable people, such as refugees. They emphasised that compared to traditional media formats, AR was more *'interactive'*, and that this could help in *'angling the participant to be in touch with the subject more'* (P1), possibly helping raise awareness of vulnerable people without tokenising their lived experience.

Several other participants described the potential uses of AR in artistic and musical contexts like *polaris~*. One participant said that AR had the potential to allow musicians to *'easily feel'* and *'play [...] with sounds'* (P2). One participant said that they could see AR being used for both instrument-building and creating installations (P3).

Safety and Accessibility

On the topic of safety, one participant expressed that despite *'[feeling] like there will be lots of benefits for [the uptake of AR and VR]'*, they believed that it could lead people to *'lose track of reality'* (P7). Overall, participants reacted positively to the fact that their concerns over the comfortability and fit of the headset would be able to be addressed thanks to the open-source nature of the NS's design.

6.4.5 Expression

Participants expressed themselves in various ways during the AR experience, and most described the ability to create visual and sonic components with their hands as the most compelling aspect of this expression. For example, one participant appreciated the variety of visual and sonic patterns that they could create: *'when your hands are together, it made one style of shape, and when your hands were away it would make different styles that affected the music'* (P7), another emphasised variety as well as exploration: *'[The experience] let me explore by using my hands [and] doing different gestures'* (P6).

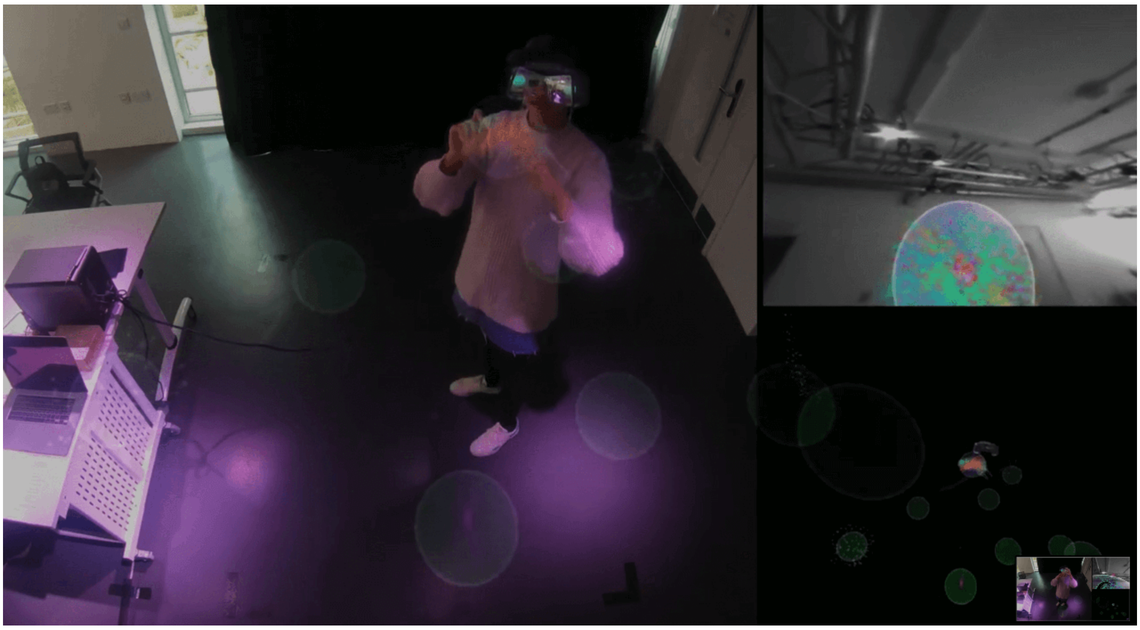


Figure 6.11: Artificial composite 3rd and 1st person views of a polaris~ participant using their hands to interact with the floating orbs (from Bilbow, 2022*a*, at 0:00)

Accordingly, several participants expressed their ability to act in the scene as *'control'* or *'power'*. One participant, almost sounding guilty, said: *'I mean, it sounds weird, but I felt, like, very powerful'* (P10). Another, remarked similarly: *'I think once I realised that I had the power to add things, I didn't let go of that'* (P3).

While one participant remarked that *'physically doing something [that] you can see the effect of'* resulted in a feeling of *'control'* (P7), another participant noted that they didn't always feel this: rather, that this might grow over time and with increased familiarity of the scene, reinforcing the suggestion of a learning process in the experience (P3).

Closely related to these codes were ones where participants expressed their wish to have more power and control over the scene, or that they had wished for different outcomes. Most common was the wish to be able to move the orbs around themselves (P3, 6, 9) or the ability to change elements as I had done in the experimental part of experience themselves, and at their own leisure (P5, 7, 9, 10).

One participant agreed that adding further visual indicators for the effects being had on the sound would help them notice these changes. The same participant commented that the pinching gesture used to tighten the stream of particles from the hand was unintuitive and would have preferred it to be a pointing gesture (P2).

6.4.6 Immersion

Awareness

Most participants reported that they felt aware of their real-world surroundings during the experience, one commenting that it was *'because you could still see everything, you could still hear'* that they didn't get *'lost'* in the experience (P7). However, one of the participants was adamant that they had *'lost track of reality'* during the experience, and that it had felt *'like [they were] in another environment'* (P9), another still, observing that there were moments when they forgot where they were (P10). It's clear then, that the experience immersed the participants, some more than others. When asked to offer a rationale for their feelings of immersion, participants pointed to several factors.

Sights

One participant noted that they felt more immersed by the visual components of the scene, but that they would have felt less immersed if there wasn't an auditory component to the experience (P10). When being immersed by visual elements, for some it was colours that maintained this sense of immersion, with one participant commenting that the *'vividness'* (P8) and size of the colours when particles had been made larger in the experimental section is what led to the moments of highest immersion in their experience.

Sounds

On the topic of immersion through audio, one participant put this down to the feeling of being *'submerged'* in different layers of three-dimensional sound (P1). Similarly, many of the participants confirmed or independently reported to be able to discern and localise the tones they heard from different orbs around them, with some doing this by exploring through movement (P7), and others taking the visual cue of the white particle burst (P3). One participant remarked that the sound was the *'main aspect'* of immersion for them, and that it made them *'feel like part of'* the experience (P4); another commented that the sound *'surrounded'* them and held their concentration so much that they almost forgot that they were wearing the bone-conduction headphones (P2). For another still, it was the activation of one of the orbs' sound effects that made them feel part of the experience (P3).

Actions

A participant remarked that it was the feeling of *'creating'* that led to their immersion. Additionally, they remarked that it was the *'element of play'* in the interaction between particles and orbs that had immersed them in the experience; further noting that it was the way that the particles *'emerged'* from their hands that kept them engrossed (P9). On playfulness and fun, another participant commented that it was the fact that they could interact with content that wasn't *'there'* which was the most fun for them (P5).

Physicality of Content

One participant reported multiple times that they could *'feel'* the button when they pressed it (although technically it was floating adjacent to their hand in mid-air). They agreed that it could be the mixture of the feedback sound, volumetric threshold trigger, and lighting that led to this effect (P9).

Another participant, upon placing their hands close to an orb remarked: *'I know there's nothing there, but when I put my hand [towards the orb] I feel like I'm going towards something warm'.* This same participant expressed a keen interest during the experimental section in drawing large three-dimensional sculptures. During one of these drawings, the participant walked around their creation, and then took a moment before exclaiming: *'Oh! I forgot that it wasn't a real thing, I kept trying to go [around] it, but I could just go through it!'.* Later, they noted: *'I guess it's about our brains. [...] When we see it in 3D we automatically think it's more real than [if it were on a screen]'* (P8).

6.5 Conclusion

Overall, the AR experience engaged participants fruitfully, with many noting their ability to express themselves audiovisually in creative ways. For *polaris~*, the ability to do so whilst maintaining a privacy-respecting and cost-effective focus, is a testament to the individual components of the framework used to create it, and the labour that has facilitated the development of these open-source solutions.

The categories of codes extracted from the grounded theory analysis have resulted in a rich set of data. From those related to participant sentiment, it's not only clear that the A/V AR experiences are able to elicit a wide variety of emotions, but that to explain and make sense of them participants often made use of metaphors and past experiences. The fact that it was expressed multiple times by participants that the experience was one that they'd never had before might be a way of accounting for this variety and overlap of emotions.

Relating to the category of learning, it's clear that participants sensed this from multiple aspects of the experience, with one pointing towards the dimensionality, and others pointing towards the interactive elements and the need to explore the scene. For one participant there was a connection between learning and immersion. Within the context of musical interfaces, this could be taken to show that viewing the participant as a learner in the experience could lead to a deeper level of engagement.

Within the category of adoption, the fact that the headset lacked a good fit for most participants was clearly what detracted from the experience most. It led not only to a reduction in experience immersion, but also to a lessening of comfort and the knock-on effect of muscle fatigue and inability to exercise full agency for some participants. From the comments on different potential applications for AR, it is clear that the offer of deeper interaction with subject matter, increased immersion in an experience, and the sense of *'feeling'* or *'playing'* with virtual content has led to participants envisaging AR's utilisation in several artistic and musical contexts. Notable was the suggestion that these facets of experience, especially that of the three-dimensional and context-specific sounds, could be employed to convey messages of socio-ethical importance as well as aesthetic experience. It is important to mention that some participants warned of negative side-effects or the potential for negative experiences in AR, showing the importance for an inclusive and safety-minded approach to designing such AR experiences.

To improve on the comfortability of the experience, the first changes I made were to design an alternate headgear section for the headset. Over the course of a day, I collaborated with another NS community member on 3D printable designs, which were merged into the main repository, and that would allow the quick and easy substitution of the main headgear piece for a smaller one that was more accommodating of smaller head sizes.

From the codes relating to self-expression and control, participants appreciated the ability to interact with their bare hands, and felt that this was the main contributor to their expression in the scene. This, for some, led to a feeling of power, and for some, a feeling of control over elements of the scene. For others, the feeling of control wasn't entirely certain, with some noting that the scene had agency of its own. It is also conclusive from these codes that some participants desired more control over the scene, although implementing this would have to be done thoughtfully, without overloading the scene with content and parameters to change.

Immersion tended to stem from the fact that the elements of the experience: sights, sounds, and actions were spatialised in three dimensions. Participants enjoyed and felt immersed by the movement and colour of the visual elements and were able to discern and localise the source of different sounds in the experience; several noting that this element was the most immersive factor for them, whilst others preferred the visual elements. Others still, noted that the actions that they employed, gestural and movement-based are what immersed them in the experience most, and for some, this led to the virtual content of the scene feeling physical at times.

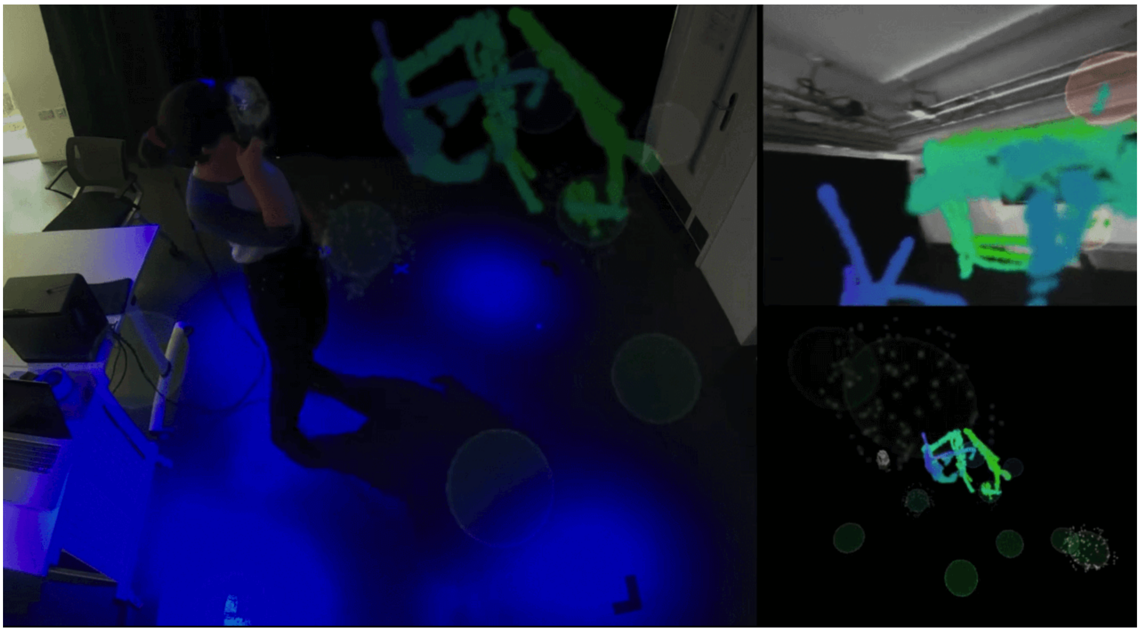


Figure 6.12: Artificial composite 3rd and 1st person views of a polaris~ participant expressing themselves in the scene, and viewing their creation from different angles (from Bilbow, 2022*a*, at 0:00)

While the above analysis is not, on its own, sufficient to draw conclusive guidelines for design, it does shed light on several connections between elements of this specific experience: learning, comfort, safety, spatial perception, visual-, sonic-, and action-led immersion, and physicality of virtual content. In Section 8.4 this is expanded upon, and this has lead to the iteration of parts of the design patterns found in Section 9.2.

7 Performing polygons~

Developing a Sound ARt Performance Practice

Blog: https://www.sambilbow.com/projects/polygons
Code: https://www.github.com/sambilbow/polygons
Guide: https://www.github.com/sambilbow/polygons/wiki
Archive: Appendix C

7.1 Summary

As a direct consequence of witnessing participants enjoyment and play with *polaris~*, I recognised for the first time looking from the outside in, that the system had a larger propensity for fostering learning, virtuosity, and depth of expression than I had originally thought; if only the experience was slightly more complex, the interactions more *nuanced*. The gestures, play, and expression by participants led to a kind of quasi-transhumanist dance, one that struck me as a technologically mediated dialogue between hybrid self and hybrid environment, a delicate balance of agency.

Until this point, I had been primarily focused on the medium as used for the composition of musical pieces e.g. *area~*, or of installation-like experiences *polaris~*. Performance with AR had remained abstract, especially as, formally, its not my preferred mode of musical expression. However, the balance of agency between participant and system, between self and environment, presented itself during the evaluation of *polaris~* to be an area ready for exploration through performance.

The following chapter outlines my exploration of a a fifteen-minute experimental A/V AR improvisation using an AR performance ecosystem called *Weird Polygons and Hand Noises*, or *polygons~* for short.

7.2 The Composition of *polygons~*

Drawing from the categories extracted from Evaluating polaris~: Results, I pursued the design of a system with physically moveable elements, audio-reactivity, and enough room to be able to learn and explore the scene both spatially and in terms of interaction and sonic palette. Thus, as an AR performance ecosystem, *polygons~* delivers this by describing the improvisational and performative relationship between a performers actions via body, hand, and head movement, feedback from the audience, and three real-time AR musical instruments: *ambi*, *click*, and *hands*.

ambi, a red wire-frame icosahedron, serves as a dual-oscillator drone synthesiser that the performer can call on my taking and bringing it closer to them with their hands. Its voice is contingent eleven real-time parameters, which are sent to the Pd patch attached to it. At specified distance two particle systems are activated from the palms of the performers hands, and the drone from *ambi* is activated. The particles are drawn to the centre of *ambi*, their paths guided by an unseen particle forcefield - the same behaviour as in *polaris~*. Real-time hand 'collision' in three dimensions with *ambi* is constantly reported per hand, resulting in two sets of

Unity Scene Attribute	**Pd Parameter**	
Hand	**via Left Hand**	**via Right Hand**
Collision Distance	Drone 1 On / Off	Drone 2 On / Off
Collision X	Reverb Amount	Drone 2 LPF CF Mod
Collision Y	Drone 1 Pitch	Drone 2 Pitch
Collision Z	Rev/Dly Amount	Drone 2 LPF CF
ambi	**via pinch gesture**	
Scale	Output Filter Cutoff	

Table 7.1: The parameter mappings for *ambi*

Unity Scene Attribute	**Pd Parameter**
click+- Distance	Impulse 1 Frequency
click- Collision X	Impulse 2 Frequency
click- Collision Y	Impulse Chorus Rate
click- Collision Z	Impulse Chorus Depth
click- Release Spin Velocity	Impulse Reverb Amount

Table 7.2: The parameter mappings for *click*

x, y, z coordinates that form part of the data that is mapped to parameters in Pd (see Table 7.1).

click, a set of two blue wire-frame icosahedra, form a feedback system between two low-frequency oscillator controlled impulse generators. The feedback can be altered by bringing the smaller icosahedron (*click*-) closer to the larger one (*click*+). *click*+- makes use of LibPdIntegration's Unity send functionality; each time there is an impulse generated, a message is sent to Unity, which triggers a shower of particles to be emitted from *click*- to *click*+ forcefield-guided cone. As the performer intervenes and creates the feedback system, the closer they bring the icosahedra together, the faster the visual particle shower becomes, and the more erratic the impulse generators feedback on each other. A further sound parameter, connected to a reverb, is mapped to the amount spin *click*- let go with by the performer. The sound palette explores a gradient from static electricity crackles to a sound akin toa car motor catching and revving up as the feedback increases.

hands constitutes the final AR instrument in *polygons*; each of the performers hands, when a virtual button besides their palm is toggled *on*, generate a highly resonant filtered white noise. The cutoff, resonance, and amplitude of this generator-filter system is controllable independently per hand, through several dynamic movement-based attributes. The filter cutoff per hand is mapped to that hand's distance to the performer's face; the filter resonance per hand is mapped to the angle from that hand's palm angle towards the centre of the performance space; and the amplitude of each is mapped to the stretching of the fingers outwards away

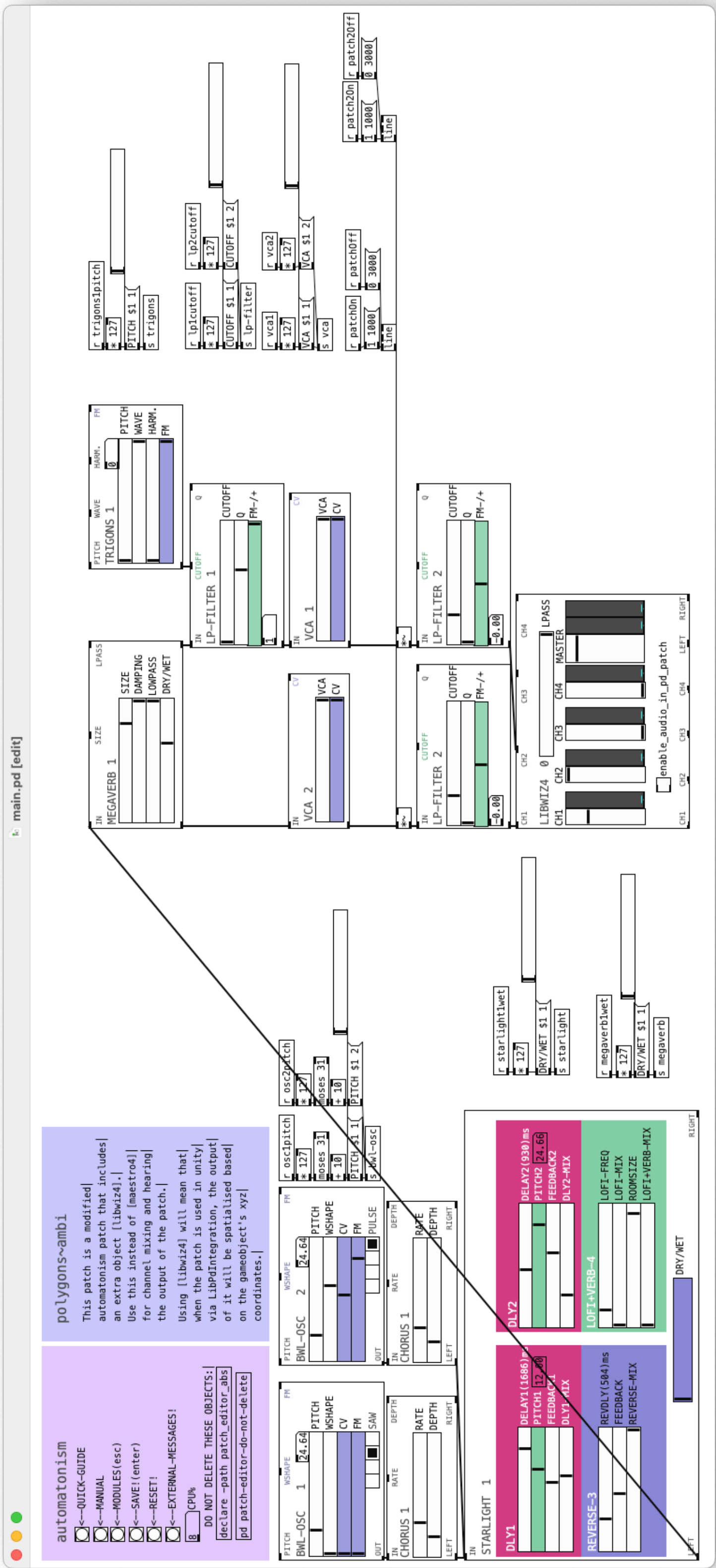


Figure 7.2: The Pure Data patch for *ambi* (code)

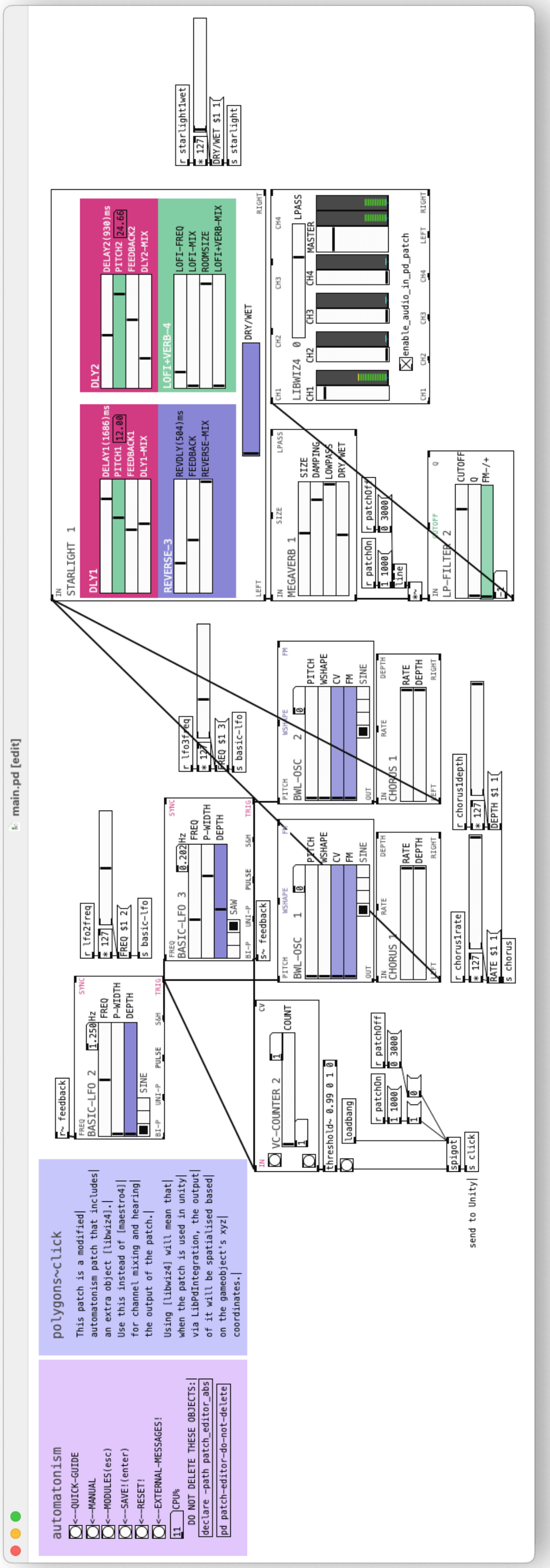


Figure 7.3: The Pure Data patch for *click* (code)

Unity Scene Attribute	Pd Parameter
hand to Head Distance	Filter Cutoff
hand to Stage Angle	Filter Resonance
hand's Finger Extension	Amplitude

Table 7.3: The parameter mappings for *hands*

from the palm. The sounds delivered by *hands* are harsh and unpleasant at certain parameter combinations and purposefully loud; from a performative standpoint, this engenders specific gestures, movements, and stances, as the performer grapples with a sonic experience akin to howling and shrieking winds.

Together, and separately, *ambi*, *click*+-, and *hands* provide a complex sound palette, explorable by the performer through non-linear combinations of hand gestures, body movements, and stances, that themselves invariably feed back into the decisions made to delve into and combine specific sounds. Visually, *polygons~* draws on the pioneering 3D wire-frame AR systems of the 20th century such as Sutherland's *Ultimate DIsplay* (1968), Jeffery Shaw's *Virtual Sculpture* (1981), and the *KARMA* system (Feiner et al., 1993*a*) (see: Figure 7.5), which were among other reasons, a consequence of computational power constraints of the time. This is juxtaposed by the fluid and visually complex behaviour of the thousands of multicoloured particles used by *ambi*, and *click*+-.

7.3 The Performance of *polygons~*

7.3.1 *polygons~*Technical Setup

From a system design perspective, as with any instrument, the importance of the performer's aesthetic experience as described the the previous section is indubitable; most of the software and hardware I had used in the development of *polaris~* was readily transferable to the context of performance. There was no need to change from the combination of Pd, LibPdIntegration, and Unity. However, when considering the design of an AR experience *as* performance, there began to surface new design considerations that needed answers:

- *By what means could I invite an audience into the hybrid space I was creating with polygons~?*
- *What elements of my experience would / could be shared with an audience?*
- *How could I go about performing an experience that I was, by now, intimately aware of, but would be difficult without context for an audience to understand?*

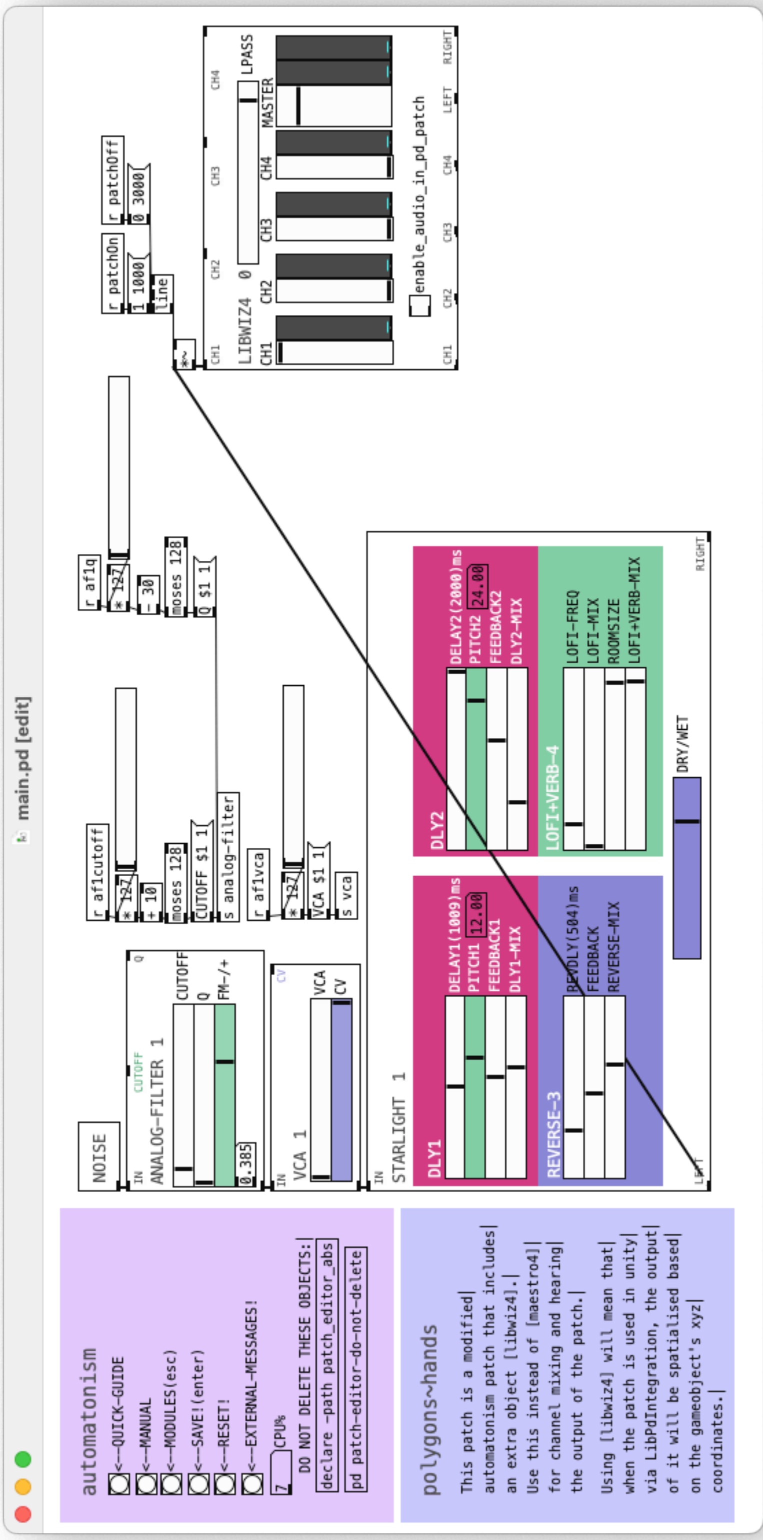
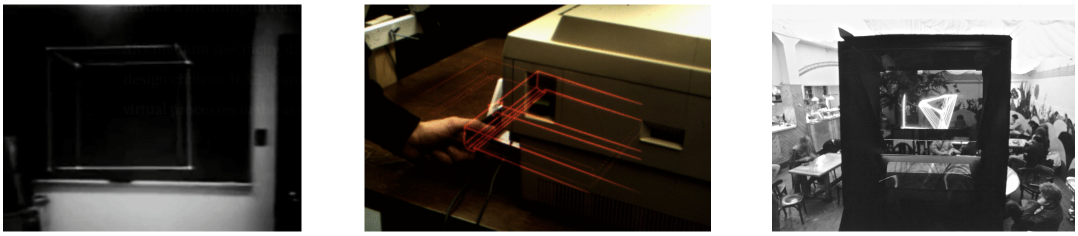


Figure 7.4: The Pure Data patch for *hands* (code)



(a) Through the 'Head-Mounted Three Dimensional Display' (in Sutherland, 1968)

(b) Through the headset of the 'KARMA' System (in Feiner et al., 1993*b*)

(c) Through the viewport of 'Virtual Sculpture' (from Shaw, 1981)

Figure 7.5: Wire-frame influences for the polygons~ instruments

Due to time constraints, the performance system I decided on was fairly simple. For translating my visual experience (I deemed this necessary for the audience to understand my gestures and their links to musical outcomes) I would project the real-time hybrid composite feed (made up of a black and white video feed from one of the head-mounted sensors on the headset with an overlay of the Unity scene) on the wall behind me. For the audio, I replaced my bone-conduction headphones (sacrificing some of my own 3D audio immersion) with the PA system of the venue. The panning would be reversed so that my gestures and movements would translate realistically to the audiences auditory perspective, i.e. the movement of my hand during the performance of *hands* across my body from left to right would transfer to the sound panning house-right to house-left rather than stage-left to stage-right.

7.3.2 The Rosehill - February 2022

polygons~ was developed for a performance as part of the seventh Experimental Music Technologies (emute) Lab showcase at The Rosehill - an independent venue, recording studio, label, creative hub, and co-working space run by artists and musicians. The Rosehill performance was the first time I had immersed myself in the *polygons~* system for an extended period of time; I had held off extended use of the system during prototyping the instruments. This lead to an authentic exploration and improvisation of the material, embodied, and spatial affordances of the three instruments, *ambi*, *click*+-, and *hands*. The combination of sharing the A/V elements of my experience, auditory immersion of the audience, and performing through improvisation, led to an intimate performance. In itself, this decision was also an improvisation, I had not practiced or rehearsed, and this was my first performance of a non-traditional instrument. This took the form of me taking it upon myself to 'showcase' the instruments to the audience, through a kind of theatrical and gestural dance that the audience were invited to be part of.

One issue I hadn't anticipated was strobe caused by feedback between the visuals behind me and the sensor cameras in the headset when I stood in the throw of projector. This combined

Figure 7.6: *polygons~* performance at the ACCA

with the otherwise darkness of the room lead to a few moments where the sensors on the headset momentarily lost calibration, moving the Unity scene contents slightly. Whilst I (and study participants) had experienced this during *polaris~*, due to the confines of the stage, and the wall behind me, this did present slightly more of a problem and limited my performance space somewhat. For example, when *click-* moved behind the wall, forcing me to stand flush with the wall and try very hard to take it out (03:30). This wrangling between the virtual and physical space presented itself as a comedic moment for the audience, and was a moment of where the mechanics of the hybrid space became obvious, and relatable despite the distance between the audience and my own understanding and experience of AR. Overall though, the performance, despite its hitches was received extremely well, with members of the audience afterwards exclaiming that they'd never seen any such kind of performance.

7.3.3 Showcase at the ACCA - June 2022

polygons~ was performed three months later at an end-of-year departmental showcase at the Attenborough Centre for the Creative Arts (ACCA) (see Figure 7.6). The space here was much larger, allowing me more space to explore (although still limited by the length of the headset cable - 2.5 metres), it reduced the chance of the aforementioned strobe, which made the sensor alignment more stable.

7.3.4 Demonstrations - May & June 2022

For furthering understanding of AR as a medium for artistic and musical practice, as well as for providing novel experiences to those who hadn't experienced AR yet, *polygons~* was made open for students and faculty to perform and experience as part of the first MAH Doctoral Conference. It was also open for experience as part of the Sussex Humanities Lab (SHL) Make & Create day, on the 25th of May, and 9th of June 2022 respectively.

These sessions provided a chance to glean some face-to-face informal feedback on the design, rationale, and sound-world of *polygons~*. Not to mention, it was an exercise in seeing second hand the amount of embodied knowledge, and skilful AR know-how I had accumulated with the system I had used for 18 months by this point. Those experiencing XR for the first time definitely struggled more with the gestures needed to move, resize, and interact with the three instruments.

7.4 The Future of AR Sound ARt Performance

From the performance of *polygons~*, it became clear to me that AR within a musical performance practice can be an effective medium for the creation of novel aesthetic experiences for performer *and* audience. However, improvements could be made to the process of 'inviting' the audience into the performer's hybrid space. *polygons~* in this regard, was fairly unpolished, even for a first performance - and I imagine the audience felt as if they were 'witnessing' rather than 'experiencing' with me. Therefore, I envisage the challenges for future AR musical performances in my own, and in the broader community's practices, lying in the development of immersive audience experiences.

With the exception of the incredible work by Amy Brandon using the METAVision headset (2018), I have been hard-pressed to find other live music performances that specifically appropriate AR *headsets* as their actual medium of performance. Despite there being an array of cutting edge performances that use AR technologies in their execution, it is extremely new as a research area, with a lot of exploration and research to be done. Like in most aspects, due to the amount of funding and earlier research focus, VR has been an area where artistic and musical performance has flourished in the last 20 years, with early pioneers (Davies, 2004) paving the way for the consideration of the body in immersive 3D space. *polygons~* could be closely linked to contemporary VR visual art making practices, where artists sculpt, paint, and draw in 3D in an infinite world canvas (Summers, 2019). AR musical performance however, is beginning to gain traction, with participatory installations (Chevalier and Kiefer, 2018), projection-based performances (Quay, 2016; Berthaut and Jones, 2016; Robinson, 2020; Larrieux and Speziali, 2022), tangible AR projects (Zamborlin, 2018), and real-time notation techniques (Santini, 2020, 2022).

As found in the field of spatial acousmatic performance (Sharma et al., 2015), a clear vocabulary ought be developed here due to the wide disciplinary scope of the technologies, aesthetics, and modes of performance explored. Indeed, the public perception of 'AR performances' has typically come to describe the use of AR as the *medium of playback* – replacing the 2D screen with an immersive 3D viewing / listening of a live or pre-recorded musical experience – rather than the *medium of performance*.

polygons~, like any prototype instrument or performance, has therefore asked more questions that it has answered. Concerning the future of AR musical performance, the present thesis proposes the following questions as potential research avenues:

- Can we avoid 'spectacle' of AR? How else can we meaningfully engage audiences who are new to AR?
- How can we invite the audience into AR musical performance more effectively?
- Is wearing more technology necessarily the best avenue for a focus on embodied performance?
- What would an AR ensemble look, sound, and feel like for both performer and audience?
- Could AR be appropriated for real-time networked performance of physically separate spaces?

Part III

DISCUSSION AND RESYNTHESIS

8 Implications for the Sonic Medium

Alice has stepped through the looking glass [...] It is the job all future artists and activists to use this technology for the better, to bring people together, and uproot social injustice.

(Skwarek, 2018)

8.1 Summary

In this chapter I aim to bring together the results of the past three study chapters, and discuss the implications they may have on what could be termed the sonic medium of AR. It is separated into three sections. In the first, I review the steps taken so far in the thesis that have allowed space for a unique positionality when considering the potential for AR as a medium for sound-driven art works. In the second, I outline the methodology that lead to the sound ARt that makes up my practice-based research. In the third section, the combined results of the previous three chapters are discussed in the context of materiality, embodiment, and space; resurfacing and re-introducing the theories explored in Chapter 3.

8.2 From Overlay to Instrument

In Chapter 1, I outlined my motivations for asking the following questions, which were addressed in Chapter 2 and Chapter 3:

1. What is AR's genealogy, historical context, its contemporary forms, trends, exceptions, and definitions?

2. What theoretical underpinnings can we use to explicate AR experiences within an artistic context?

the present thesis began in Chapter 2 with an exploration of the landscape of historical and contemporary AR research and development spanning the past thirty years. Common forms, such as headset-, handheld- and projective-based AR were outlined, as well as typical sensory displays, allowing interaction and feedback with the visual, auditory, touch-based, and smell and taste senses. Furthermore, the processes by which AR mediates reality were laid out using Schraffenberger's categorisation of relationships and AR subforms: augmented, diminished, altered, and hybrid reality, as well as extended perception (Schraffenberger, 2018). Despite this wealth of possible avenues for AR experience composition, the paradigmatic form of AR we hear about or see are predominantly characterised by being *visual displays that overlay information*. Thus far in the thesis, this has been referred to as ocularcentric layering paradigm, or typical AR. This can be explained by a number of phenomena, but examining the origination of AR in the MIC by way of U.S. Defence funding, it is not a surprise. This has had a compounded effect on the forms that AR finds itself being co-opted for in the arts. Several creative and expressive works were explored, that engaged in AR because of its ability to sensorily engage participants, induce rich aesthetic experience, enable collaborative expression, and empower new forms of agency and activism. Nonetheless, there are but a few examples of sound art AR experiences in comparison to visual counterparts because of the typical form of AR.

In proposing the development of AR as a medium for the creation of immersive sound artworks, its use as an instrument, or tool for sound art installation, I drew on several areas of importance in Chapter 3, first aesthetic experience and the '4E's', and then materiality, embodiment, and space. It began with a grounding in the concept of 'art as experience', drawing from the work of (Dewey, 1934). Dewey states that the capitalistic reverence of fine art, notably by the 'nouveau riches', has led to art being put on a pedestal - disconnecting it from its origin and operation in the everyday experiences of people. Leddy and Puolakka have since proposed that 'material of art should be from all sources and art should be accessible to all' (2021). Dewey points towards the aesthetic experience that art entails, and notes that the 'live creature' is inseparable from the environment in which they are embedded. Today, despite social media as a platform for cultural production of artistic works has some merits, the fabric on which it is built is no different from the capitalist mechanisms that separated art from experience in the first place. Thus, open-source, hacker, DIY, and maker approaches were proposed as a method of democratising 'all sources' of art, and attempting to increase accessibility. The focus on the body by Dewey also points towards the move towards tangible interface development, participatory design, and human-centred design that were outlined in Section 4.2.1. To delve deeper into this experience of art, I proposed an enactivist approach to considering cognition in experience. Often called 4EC, it states that cognitive process are embodied, embedded, enactive, and extended (Gallagher, 2017). In considering the design, performance, and experience of AR, 4EC offers a fresh perspective on concepts such as agency, action, perception, immersion, and spatial engagement.

The first theoretical lens through which to examine AR's design in computational art and music practice involved outlined the importance of a complex systems framing of interface use and performance. I drew on existing research from the field of digital musical instrument design (Magnusson, 2009*a*; Di Scipio, 2003; Essl and O'Modhrain, 2006; Armstrong, 2006; Hayes, 2019; Chevalier and Kiefer, 2018) in order to demonstrate the usefulness of considering the material of performance systems as complex, and ecosystemic. To examine what happens in the experience of participants, the second lens was one that took seriously the assertions of 4EC, namely that cognitive processes in experience are embodied, embedded, enactive and extended. I draw from multiple disciplines of similar theoretical and practical work in VR and AR to show how 4EC offers a novel framing by which to consider the experience of AR by participants, audiences, and performers. Closing out the trio of theoretical lenses, is a grounding of the aforementioned consequence of AR for the experience and construction of 'space'. I first critically examine the term 'Metaverse' (Stephenson, 1992). Its modern-day origin is in technologies like AR and VR, which in turn sprung from' deep within the military and Western - scientific - industrial - patriarchal complex' (Davies, 2004), and its current operation has been heavily co-opted by cryptocurrency projects. Because of this, in its current state, the 'Metaverse' is hardly fertile ground for the 'live creature' to experience art 'accessibly', and from 'all sources' (Dewey, 1934; Leddy and Puolakka, 2021), indeed, it mirrors the exact profit and exploitation motive of the historical context it originated in.

8.3 Engaging in a DIY Approach to Sound ARt

A clear positionality from within the arts, one that stands in contrast with the militaristic and industrial applications and their effect on the typical form of AR technologies was outlined in Chapter 4. This chapter proposed methodological approach to compose, iterate, and perform sound ARt that would allow the addressing of the following research questions through practical contributions to the field of interactive music systems:

3. What are AR's boundaries and affordances as a medium, are there problems it poses artists and musicians?
4. What is the resultant experience for participants and audiences (or 'immersants') of an artistic AR experience?
5. What might a future corpus of artistic AR experiences and digital music instruments look, sound, and feel like?

This began with the explication of the concept of resistance, and its importance in my rationale for choosing specific methods. Specifically, I highlighted the role of AR's paradigmatic form as a closed-source consumer technology, as a visual technology, and, and as a medium that overlays information, as primary motivators and areas for change in the field. In practice, this approach led to the evaluation of three aesthetically, functionally, and methodologically distinct interactive music systems over the course of the thesis, *Composing area~ (2020)*, *Evaluating polaris~ (2021)*, and *Performing polygons~ (2022)*. These experiences, or sound ARtworks were developed using a set of design patterns that were iterated on over the course of the thesis, and will be outlined in Section 9.2.

There are clear limitations to the the generalisability of specific findings in the AR experiences developed. Having to adapt to the COVID-19 pandemic meant developing methods that revolved more around autoethnographic / autobiographical study of the systems. This, while potentially offering more depth of insight over long-term deployment of *area~* for example, don't provide the kind of breadth of insight that the participant studies in *polaris~* did for example. Qualitative analysis, while conducted with rigour throughout the thesis, still only speaks from a position that highlights the subjectivity of participant experience, and specificities of the experience being examined. There are, as always, positives and negatives to this. While providing considerable retrospective insight into my own creative practice, and providing the groundwork for developing the theoretical propositions in the next section, and patterns in Section 9.2: Design Patterns for Sound ARt, they do not provide any objective and generalisable results about the nature of experience or reality. Perhaps there is no such thing, and the immense diversity of possible AR experience serves to demonstrate this. Another benefit of the research methods involved in this approach is their propensity to provoke and generate questions, which have surfaced throughout this thesis.

8.4 Examining Sound ARt Experiences

8.4.1 Combined Results: *area~*, *polaris~*, and *polygons~*

The previous three chapters outlined the experiences, compositions, performances, and results of engaging with AR as a medium for sound ARt production. In this section I would like to briefly touch on the findings from each.

area~

area~, which could be classified as a pilot study, or a research probe into the possibilities of non-visual AR experience, uncovered the following results from an ABD research method. Firstly that the blending of *real and virtual auditory environments* resulted aesthetically in the creation of a third, augmented environment that was greater in experiential nature than the sum of its parts (not simply a combinatorial layering). Secondly, the ability to spectromorphologically manipulate sounds in real-time in this augmented environment with the body proved an engaging compositional tool. Lastly, the potential for creating believable illusions of real-world sound sources from these manipulated and spatialised virtual sounds was highlighted.

polaris~

polaris~, through the evaluation of participant studies, and use of the grounded theory analysis method, found that A/V AR experiences are able to elicit a wide variety of emotions, and to explain and make sense of them participants often made use of metaphors and past experiences. Learning was one of the categories participants described, and it was clear that participants sensed this from multiple aspects of the experience, with one pointing towards the dimensionality, and others pointing towards the interactive elements and the need to explore the scene. In terms of adoption and comfortability, the fact that the headset lacked a good fit for most participants was clearly what detracted from the experience most. It led not only to a reduction in experience immersion, but also to a lessening of comfort and the knock-on effect of muscle fatigue and inability to exercise full agency for some participants. From the comments on different potential applications for AR, it is clear that the offer of deeper interaction with subject matter, increased immersion in an experience, and the sense of *'feeling'* or *'playing'* with virtual content has led to participants envisaging AR's utilisation in several artistic and musical contexts.

Control and self-expression was among the most highlighted categories, participants appreciated the ability to interact with their bare hands, and felt that this was the main contributor to their expression in the scene. This, for some, led to a feeling of power, and for some, a feeling of control over elements of the scene. For others, the feeling of control wasn't entirely certain, with some noting that the scene had agency of its own. It is also conclusive from these codes that some participants desired more control over the scene, although implementing this would have to be done thoughtfully, without overloading the scene with content and parameters to change.

Immersion tended to stem from the fact that the elements of the experience: sights, sounds, and actions were spatialised in three dimensions. Participants enjoyed and felt immersed by the movement and colour of the visual elements and were able to discern and localise the source of different sounds in the experience; several noting that this element was the most immersive factor for them, whilst others preferred the visual elements. Others still, noted that the actions that they employed, gestural and movement-based are what immersed them in the experience most, and for some, this led to the virtual content of the scene feeling physical at times.

polygons~

polygons~, the last of the experiences, could be described as a first look (or listen) into the implications of sound ARt performances. For me, it provided a new, visceral type of embodied performance and led to a kind of 'technologically mediated dialogue between hybrid self and hybrid environment', which in itself demonstrated the delicate balance of technological agency and sense of 'uncontrol'. It provided me with the resulting questions:

- Can we avoid 'spectacle' of AR? How else can we meaningfully engage audiences who are new to AR?
- How can we invite the audience into AR musical performance more effectively?
- Is wearing more technology necessarily the best avenue for a focus on embodied performance?
- What would an AR ensemble look, sound, and feel like for both performer and audience?
- Could AR be appropriated for real-time networked performance of physically separate spaces?

8.4.2 Augmented Materiality: The Relational Fabric of the AR(tistic) Medium

Core to my own approach is, as I'm sure is evident by now, is the centring of the notion of the processual nature of AR systems. Ocularcentrism and the additive layering paradigm have shifted discussion of AR systems towards an object-centred view of the 'reality' that they present, this effect is also present in VR (Hovhannisyan et al., 2019). In *Composing area~*, *Evaluating polaris~*, and *Performing polygons~*, it was demonstrated that an AR object is not a static visual thing with marked boundaries, not in any meaningful way to the artist/designer at least. It ought rather to be thought of as an on-going and distributed component existing inside a dynamic web of experience and meaning; and as such, any discussion of the contents or material of an AR composition ought to be considered through this lens. Even a single apparent 'virtual object' that is in front of a participant is not *just* that; it is an invitation, a handle, a real-time process by which a participant can be perceptually guided through sensorimotor action towards a specific aesthetic experience. This so called 'object' might be part of a larger organised whole, a component of a room-scale musical experience for example, or an emergent property of a hidden set of complex conditions that have only just been met through the specific movements of a participants body. This, more holistic, view of AR processes allows for a more fruitful discussion of the types of experiences we can expect to craft as AR practitioners; and engages more critically with Schraffenberger's taxonomy of AR relationships.

Embedding Schraffenberger's fundamental relationships (Table 8.1) within Di Scipio's notion of an 'ecosystemic' musical interface, or Water's 'performance ecosystem', as outlined in Section 3.4, could consist in viewing the AR process as a real-time network of interactions

Relationship	Description
Coexistence	Unrelated
Presence	Spatially Related
Information	Content-Based Relationship
Physical	Affect Each Other
Behavioural	Sense and React to Each Other

Table 8.1: Schraffenberger's Fundamental Relationships

distributed across the 'hybrid' brain - body - environment. This helps us in identifying the *medium specificity* of AR, and how it may uniquely be deployed to create meaningful sound ARt. If the motive for the composition of an artwork is to intentionally impart knowledge, meaning, or truth through aesthetic experience these must exist within and across the above network of interactions and relationships in our brain - body - environment distribution. I suggest that for the time being, we view this latent aesthetic experience as an real-time interaction between the components of:

- Intention - the intended meaning behind the composition of the piece
- Medium - the specificity of the apparatus by which this meaning is imparted
- Experience - the on-going process by which the medium is engaged with by the participant
- Realisation - the resultant knowledge, truth, or subjective experience from of the above

In Section 3.2, we proposed that from Dewey's perspective, an artwork ought also to originate and operate within everyday sociocultural life in order to bring about positive social change through aesthetic experience. These concerns could be conceived as mainly arising from the component of intention, and its dynamic interaction through the medium into experience. Concerning the physical, or indeed virtual, manifestation of these intentions is that of the material composition - which is facilitated by the medium and its materiality. Of course, a consideration of the composition of a work cannot be divorced from the real-time experience of a participant, but from the perspective of the artist wanting to engage in these tools, an understanding of the inherent nature of the medium of AR is necessary. Realisation of specific messages in the experience of artistic works could manifest in various ways, but one could argue that 'the aesthetic experience' of the artwork has the potential to incur a feedback loop in which the participant is in a constant state of realisation, due to the nested, non-linear, and explorative aspects of the instrument or experience - drawing from Armstrong's realisational versus functional interface (2006). Perhaps they even come away from the artwork, imparted with changed beliefs or outlooks on the content of the experience; and then go on to act on these beliefs within their sociocultural life, thus leading to others potentially changing their own beliefs too.

In relation to the above constituent parts, in the context of Schraffenberger's relationships, what defines AR's medium specificity when chosen for the creation of expressive works of art, and how can these relations provide fertile ground for a new aesthetic of composition? The key element of these relations I argue, is the underlying assertion that what makes AR unique is its ability to modulate the perceived conceptual 'distance' between real and virtual elements in three-dimensions and in real time. In Azuma's (1997) original definition of AR, this is referred to as the 'registration' or 'alignment' of virtual content to real world content. I argue that Schraffenberger's fundamental relationships expand this concept beyond just a spatial alignment of elements. Presence-based relationships modulate this spatial distance between elements, while Information-based relationships modulate the thematic distance, Physical relationships modulate the material distance, and Behaviour-based relationships modulate the ecological distance.

The narrative around the modulation of these various conceptual distances between real and virtual processes inevitably tends towards the closing of the gap between them. After all, the industries developing AR view this as the 'issue' of registration - the virtual and the real must be brought closer together. A U.S. marine wearing an AR headset that provides him with a psychedelic experience of the true interconnectedness of all of reality, by exposing the incongruencies in our sensory stimuli through multisensory artwork that exploits and widens these conceptual distances, is a sure-fire way of Microsoft not being awarded any U.S. Army contracts in the future.

For a slightly more technological example, the resolution and acuity of motion and tracking sensors, normally viewed with the purpose of achieving an AR that is spatially aligned to the perceived reality of the physical environment of the participant - thus closing the spatial distance through a Presence-based relationship between that 'virtual object' and the physical environment. Another example might be an audio-tour. In this example, an Information-based relationship is invoked by closing the 'thematic distance' between virtual and real components, here, an abstract informational audio script becomes embedded in the actual environmental content of its real world setting. Schraffenberger argues that real and virtual objects casting shadows on each other constitutes a physical relationship - I'd argue that it is key to also view it as a reduction in the perceived material distance between the two objects (the way in which their physical matter behaves in respect to each other converges on the expected outcome of if both objects were physically real). Also proposed is that a virtual animal reacting to real world sounds would constitute a behavioural relationship - as you might expect, I'd argue that it must also be viewed as constituting a reduction in the perceived ecological distance between the animal and the sound (the set of behaviours that constitutes the interrelation of both environments converge on the outcome that would be expected if both animal and sound were members of our physical reality). These discussions of what I term 'closing the gap' usually fall under the banner of the drive for 'increased immersion' or 'believability'.

However, just as AR is demonstrated to be able to close the spatial, thematic, material, and ecological distance between the virtual and the real, so too can it further the gap between them. This is what Schraffenberger encapsulates in her argument for the proposal of the 'relationship between the real and the virtual' to replace the proposal of the 'registration of the virtual to the real' by Azuma among others. What if the thematic distance between the real and virtual is radically increased, but all others are kept the same? Could this be exploited for aesthetic effect? For artists using AR, this is an important consideration — along with their definition of 'real': is it synonymous with 'truthful', 'physical', 'tangible'? What is the resultant aesthetic experience of participants if the virtual content of the artistic or musical AR scene is divorced from the expectation of how a physical counterpart engages with space, theme, matter, and ecology? What about when going beyond representations or remediations of existing physical objects and processes, and presenting participants with radically novel virtual processes that still seem to be 'embedded' in our physical reality via these technologies?

From this line of reasoning, the medium specificity of AR could be said to be its 'invocation of a performance ecosystem constituted of relationships between real and virtual processes in the axes of spatial, thematic, material and ecological distance'. If these relations are in turn experienced by a participant whose cognitive processes are embodied, embedded, enacted, and extended, it may stand to reason that the closer the distance between physical and virtual elements on these axes, the less discernible 'physicality' and 'virtuality' may become, and the cloudier the boundary between them. Despite being slightly alarming, this isn't to make the argument that a 'virtual piano' might ever be mistaken for a 'physical piano', but I believe that the claim could be made that given enough time, a participants notion of what is 'real about a piano' has the potential to be modulated, given that the virtual piano is at some level altered to be incongruous with its physical counterpart, but on most axes indiscernible from it. Perhaps it may look the same, but behaves differently, e.g. the keys play from high to low when pressed right to left. In this way, for a participant, the meaning and concept of a piano could change through this broader process of sensory or perceptual illusion, and then have real consequences in the physical world. This is a fairly benign example compared to what may be possible with future AR technologies, and I view this as an important consideration for artists to hold: what are the ethical considerations I need to make as an artist who is using technologies that enable experiences such as this? What platforms am I using, and is telemetry gathered for a corporation of the technology that I am using? If AR experiences are asking participants to suspend their disbelief in exchange for new realities and beliefs, as artists we must be clear on what these beliefs are, and how they might be realised after the experience, in the actions of participants. This is explored further in the section of the chapter on space.

As artists and musicians, I would argue that a focus on providing multisensory engagement in an AR work be of paramount importance in most of the above considerations. This not only provides more channels through which to modulate the distances described found in Schraffenberger's relationships, but also widens the broader ecosystem of interactions possible for an enactive participant of their hybrid environment. This is nature of human experience proposed by 4EC - that the participants of an AR experience are embodied beings that cognise through perceptually guided action that is in turn afforded by their sensory paraphernalia. Chevalier and Kiefer argue that this highlights that AR is 'inseparable from a multisensory ecosystem, inhabited by modes of sensing, modes of perceptual mediation, computational relationships between sensing and mediation, human participants and their environment' (2020, p. 4). This gestalt, you could refer to it as, when viewed through my own ecosystem approach to AR taken in *Composing area~*, *Evaluating polaris~*, and *Performing polygons~* constitutes the relational distances of spatial, thematic content in AR.

In her taxonomy, Schraffenberger describes these as Presence-based, Information-based, Physical, and Behavioural relationships. These fundamental relationships underlying the experience of an AR participant could be said to have been founded in the artist's intention to construct a performance ecosystem that contains whose material is constituted by varying conceptual distances between real and virtual processes in the axes of space, theme, material, and ecology.

8.4.3 Augmented Embodiment - Aesthetic Experiences of Embodied Systems

The relationships, distances, or what I will refer to as the augmented materiality of AR, exists outside of the realm of in-the-moment agency for a participant, in some kind of representational or intentional belief-system of the artist. They are not the actual handles by which a participant perceptually guides their actions. Instead, those affordances are based in the hybrid real / virtual reality that emerges from said relationships or performance ecosystem. Schraffenberger describes these as 'AR subforms'. These processes of reality modulation are what could be seen as the ideal ground through which to bring art back to the origin and operation of everyday life. This is because they explicitly engage the participants embodiment, inviting what could be called augmented embodiment - a concept touched on in Section 3.5.2.

If we take seriously this proposed model of AR — that the resultant experience of participants is one that constructs a complex system of simultaneously real yet virtually modulated, subverted, augmented, or diminished hybrid environments — it follows that these environments provide a hybridity of options for new modes of perceptually guided action. Moreover, taking 4EC as a basis for understanding an audiences experience of such dynamic relations, and defining AR as 'real-time computationally mediated perception' (Chevalier and Kiefer, 2020), it follows that AR has the ability to afford novel modes of aesthetic experience that affect our cognition. Through this intertwining of real and virtual processes in the enactive space of participants, AR presents an opportunity to uniquely render the typically invisible, unheard, and intangible tensions and injustices in our everyday cultural, socio-economic, and environmental realities. For the artist, AR offers itself as a novel medium for such creative work - these tensions and injustices having long been one of the central narratives of artistic production.

Employing AR then, means constructing realities, this is proposed by Schraffenberger as 'AR subforms', which extends the definition of AR - towards a system that encompasses a variety of hybrid (real/virtual) processes that occur *in* experience. Most of these subforms, all of which were outlined in Section 2.5, have seen nascent use in AR applications, not least in the arts. Due to consumer AR devices mostly taking the form of a headset or screen with either a camera feed-through or optical reflection techniques (visual see-through or optical see-through), most applications fall into the category of the literal 'augmenting' of reality, that is, to add to reality. However, as I have outlined and exampled, there are other modes of perceptual modulation that necessarily fall under a broader and more holistic AR definition such as Chevalier and Kiefer's 'real-time computationally mediated perception' (2020). In *Composing area~*, *Evaluating polaris~*, and *Performing polygons~*, I endeavoured to develop more than an overlay of visual sensory stimuli, by necessitating the movement or interaction of the participants body, and could therefore be seen as a form of altered or hybrid reality.

The AR subforms in question (Table 8.2), deal in the addition, removal, transformation, completion, and translation of environmental aspects through which a performer or participant's actions could be perceptually guided — an ecosystem of hybrid processes that are spatially (localised), thematically (contextually relevant), materially (are in/congruently tangible), or ecologically (reactive to environmental cues) embedded within their physical environment.

Subform	Description
Extended Reality	The Virtual Supplements the Real
Diminished Reality	The Virtual Removes the Real
Altered Reality	The Virtual Transforms the Real
Hybrid Reality	The Virtual Completes the Real
Extended Perception	Translating the Imperceptible

Table 8.2: Schraffenberger's AR subforms

What happens in these processes? What do they invite or necessitate a participant to think, do, and believe? Drawing more analytical depth from the six main assumptions of a 4EC approach to experience as detailed in Section 3.3, we can ask the following questions in order to develop direction for further understanding of the nature of the network of a participant or performer, an instrument or experience, and their environment:

- In what way do the artistic choices that produce different AR subforms, e.g. hybrid reality, diminished reality, result in varied initial conditions for the emergence of cognitive processes, e.g. learning, beliefs, affect, expectation, memory?
- If the world is structured by cognition and action, which are in turn perceptually guided, in what ways do different AR subforms promote actions that disrupt, draw attention to, or re-structure this environment?
- Can specific AR subforms provide aesthetic experiences that disrupt the notion of representation mapping, internal models, and the standard cognitivist model?
- How the can disruption of brain-body-environment coupling be operationalised to promote the emergence of new (inter)subjective and culturally situated musical meaning?
- How do the different subforms specifically facilitate embodied knowledge, as it pertains to the performance or experience of artistic works?
- Do the specificities of particular subforms of AR provide varied propensities for higher-order cognitive functions, e.g. does diminished reality lead to specific instrumental know-how?

From a 4EC approach, these above situations provide us with an interesting question: if the means by which aspects of the physical world is sensed can be obfuscated to an extent that removes said aspect, in what meaningful way can the participant's action in relation to it be perceptually guided any more? What about in cases wherein sensory mediation results in the transformation or 'completion' of an aspect; in what ways does a participant's action potential change; how does this affect higher-order cognitive functions such as sense-making in relation to it? Does this lend credence to the notion that specific AR processes have the ability to construct new realities, rather than just provide illusions over the top of existing ones (Chalmers, 2022, p. 230)? If a participant of an AR musical experience, or a performer of an AR musical instrument engages with this plurality of perceptual mediations, might the addition, removal, transformation, and completion of aspects of the environment have the potential to alter their own embodiment, relations to their environment, and their enactive potential in specific areas of a space? If so, this particular method demonstrates a radical method of disrupting, or provoking new self-organised states between the real and virtual nodes of such an embedded performance ecosystem.

8.4.4 Augmented Space - The Construction of AR Hybrid Spaces, and Avoiding The Snow Crash

As we saw in Section 3.6, from a digital humanities perspective, the promised definition of 'The Metaverse' (see blending of physical and virtual human existence) is really only a rehash of already established philosophies on technological embodiment and theories of space, but plated up with generous lashings of neoliberalism, and served fresh to attract new venture capital. As such it can be readily (perhaps cynically) dismissed as a a co-opted marketing buzzword [1] that has little meaning and relation to the concepts, technologies, and labour that are ushered under its umbrella for the sake of technological progress, here synonymous with capitalist growth. These philosophical grounds will be explored in the following section, where I set out a perspective on how AR's use as a medium for computational art and music could lead to the co-construction of new, hybrid spaces wherein novel, existing, hidden and suppressed realities can be acted out anew. Lev Manovich, terms this 'augmented space', and defines it as 'the physical space overlaid with dynamically changing information [...] likely to be in multimedia form and often localised for each user' (Manovich, 2006, p. 2). The material and embodied nature of nascent XR technologies provide a new urgency to the consideration of what these spaces will be like to inhabit; who will construct them; to what extent they rely on surveillance technologies; who holds the keys with regards to software and hardware production. In the following section, the use of 'augmented space' should be read as giving emphasis to the ecosystemic nature of AR's real and virtual processes and subforms thus far highlighted in the thesis.

This section is not concerned with the creation of, or contribution to 'the Metaverse', at least

[1] see also Internet of Things, Artificial Intelligence, Machine Learning, 5G Networking, Blockchain

in its current state, rather, it views novel art and music composition with AR a fertile ground for the staging of tactics, using Michel de Certeau's phrase, to 'unsettle and diverge from the conventions' (1984, p. 36) of such heavily consumerist spaces. By placing importance on the embodied experience, and through creating novel and interactive aesthetic realities, the artist, musician, designer fosters strong and dynamic links between participants or performers and their environment - co-constructing socially and / or culturally significant 'augmented space'.

De Certeau makes a clear distinction between place (lieu) and space (espace): 'space is a practiced place' (1984, p. 117), and embeds this within a linguistic context, 'in relation to place, space is like the word when it's spoken, that is, when it is caught in the ambiguity of an actualization', 'stories thus carry out a labor that instantly transforms places into spaces or spaces into places' (p.118). For de Certeau, place is constituted in the calculations of those with 'will and power' (often institutions) to exert and isolate it (what he calls strategy), and as such, place 'implies an indication of stability'. In contradistinction, space exists within the 'polyvalent unity of conflictual programs or contractual proximities', and is 'actuated by the ensemble of movements deployed within it' and is thus subversive and operational; the result of 'calculated action determined by the absence of a proper locus' - or 'tactics'.

Henri Lefebvre takes a comparatively more phenomenological perspective, and therefore perhaps more aligned with a 4EC approach to the spatially embedded nature of lived experience. He argues that 'space is socially constructed', and that it is an 'emergence' of the 'social and mental' that is 'produced' (1991, p. 260). Lefebvre argues that space 'embraces a multitude of intersections, each with its assigned location' (p. 33) these are named in his conceptual triad:

Spaces	Forms	Modalities	Equivalents
1st	**Spatial practice** [*pratique spatiale*]	**perceived** [*espace perçu*]	subjective | real everyday live/nature
2nd	**Representations of space** [*représentations de l'espace*]	**conceived** [*espace conçu*]	objective | imaginary urbanism/cartography
3rd	**Representational spaces** [*espaces de représentation*]	**lived** [*espace vécu*]	collective | symbolic lifeworld/culture

Table 8.3: Lefebvre's 'Triad of Spaces' (in Günzel, 2019)

Thus, de Certeau's distinction of space from place, whilst valuable insofar as it indicates the imbalance between human actors and institutions within the socio-cultural context - 'the street, defined by urban planning is transformed into a space by walkers', in itself is hardly a novel realisation. Furthermore, its fecundity diminishes with the assertion that this relation should be understood solely through a linguistic lens, i.e. the rules of 'place' are written by those with power, and 'space' is the result of actions by participants reading and interpreting those rules. To view the relation as such is to say that the actions of participants must always lie within the diktat of place, and thus asserts that space originates in place and is therefore inseparable - 'the only freedom you have is to formulate alternative sentences' (Vermeulen, 2015).

As Vermeulen further notes, for de Certeau, 'space is an inter-subjective activation of a static site, a place', whilst for Lefebvre, 'place is the momentary suspension of a social flow, [a] space'. This leads to a contradiction in the formulation of 'agency' as a concept: 'de Certeau understands agency as the enactment of a script not our own, whereas Lefebvre sees it not as a container for action but as the construction of action itself.'

It's clear that with respect to 4EC approach to *live* aesthetic experience it may be difficult to reconcile the 2nd and 3rd spaces of Lefebvre's triad (conceived and lived), due to its own anti-representationalist standpoint. However oppositional on that front however, Lefebvre's argument, through the prominence of social and class struggle under capitalism underpinning its formation, does indeed align itself with certain components (embodied, embedded) of enactivism: an approach that emphasises 'the extended, intersubjective, and socially situated nature of cognitive systems' (Gallagher, 2017, p. 6):

> 'The relationship to space of a 'subject' who is a member of a group or society implies a certain relationship to [their] body and vice versa.' (Lefebvre, 1991, p. 40)

Additionally, Lefebvre's 'own particular brand of Marxism which stressed the importance of everyday life' (Merrifield, 1993, p. 8) could be seen as aligned with Dewey's own assertion of the importance of artwork to return 'origin and operation' in everyday experience. In this way, the construction of 2nd and 3rd space doesn't necessarily have to fall fully under the remit of 4EC to explicate in real-time or live experience, rather, they may constitute the socio-cultural, and environmental aspects (norms, values, laws, traditions, and conditions), as well as higher-order cognitive functions (meaning, and interpretation) that form the 'environment', as it is then to be experienced *or* later considered by the enactive cogniser.

Thus, whereas 'the Metaverse' is somewhere to 'show off your possessions', and 'maybe even' stage social interaction (Marr, 2022), augmented space in contrast, prioritises the social, cultural, and aesthetic experience of the everyday. Architecture in 'the Metaverse', due to its origin in a capitalistic conception of society and technology, alienates its own inhabitants, since 'under capitalism, it is only only through that [market] mediation that humans interact with buildings at all' (Miéville, 1998, p. 18). China Miéville's critique here of physical architecture under capitalism could also be applied to the profit motivation for the commodity fetishisation of art in NFTs and hence the Metaverse. Not just 'virtual land', but digital art, music, video games, and social connection itself. More broadly, his 'Marxist phenomenology' argues that to focus entirely on the physicality (of architecture in his text) is to 'ignore the profound experiential ramifications' of living in a social system where such commodities are exchanged for profit.

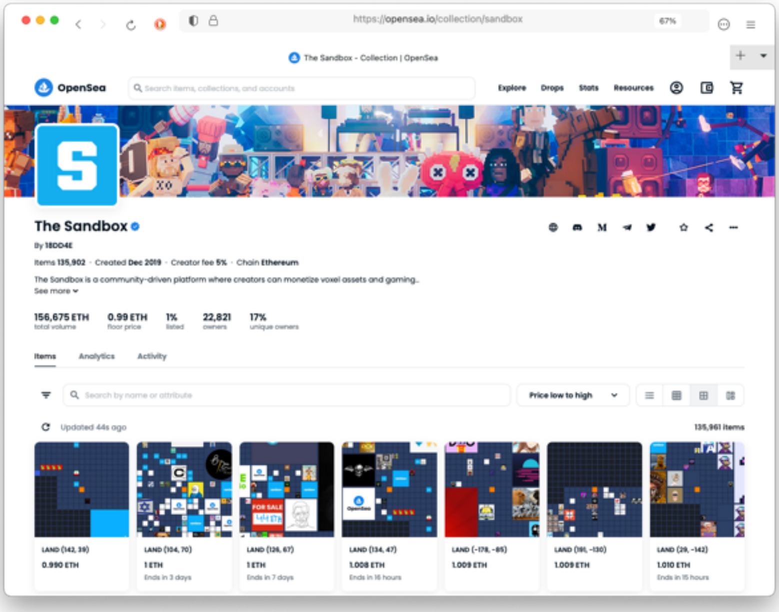


Figure 8.2: 'Space' for sale in 'The Metaverse' (from OpenSea, 2022*b*)

In stark contrast, architecture in augmented space consists in a constantly unfolding dialogue between humans and their environment, as perceptually guided by an ecosystem of hybrid processes; rather than consisting in alienation, and the 'anxiety' induced by the commodity fetishism underlying capitalist profit motives. Application of Lefebvrian spatial theory indicates that AR can be a real force for social change, due to the way it can intervene spatially in the perception of participants, leading to new spatial characteristics and possibilities. When this is taken into action by people, either audiences, or performers, it puts the decision of when and where to 'momentarily suspend' the social flow of space – and thus construct 'place' – in their hands and in their bodies.

When Manifest.AR virtually trespassed the MoMA with invisible and intangible AR art (Veenhof and Skwarek, 2010); when #OccupyAR broadcast the disembodied voices of geographically separated activists into Wall Street (Skwarek, 2018); when Cem Kozar and Işıl Ünal (2011; 2018) revealed the unseen urban dynamics of the city of Istanbul, it was through the live co-construction of new hybrid spaces — augmented spaces — that once hidden realities could be enacted anew. Whilst one might see parallels between these actions and what de Certeau terms ‘tactics’, the former, however, do more than just subverting place ‘proper’ through ‘alternative sentences’ to borrow Vermeulen’s phrase. In actuality it is far more radical. Through the dynamic relations present in its hybridity — its incessant movement — emergent and novel states of self-organisation can occur within its constituents part(icipant)s. New socio-cultural meaning through sensory, perceptual and environmental modulation have the potential to synthesise from this ongoing process. In this momentary suspension of a social flow, ‘place’ is co-constructed and enacted by the participants of the MoMA, Wall Street, and Istanbul. In the composition, experience, and performance of *area~*, *polaris~*, and *polygons~* I glimpsed a part of this possibility.

9 Conclusion

'The image with which the artist works to realise his or her idea is no longer a phantom, it can be touched, navigated and negotiated with.'

(Ryan, 1991, p.5)

9.1 Summary

There is no doubt, that AR is one of the most exciting forms of technology on our horizon as artists and musicians. In this thesis, I hope I have portrayed this, with sufficient rationale, and explanation. However, there do exist significant problems; its origin in the U.S. MIC, as a tool for enabling neo-colonialism and the streamlining of workforces by increasing efficiency. Moreover, the threat of mega-corporations on our digital freedom, safety, and rights to privacy is beginning to surface in discussions regarding 'the Metaverse' - the supposed site of XR development. In stark contrast, federated and open communities like those that ActivityPub and Matrix provide, enable new and exciting ways to shift away from these platforms and the algorithmic harm they inflict. As such, open-source tools have provided much of the ability to carry out this research, and I would again like to thank those in the community that have helped: namely those involved in the NS, LibPdIntegration teams.

The present thesis has presented three practical contributions to embodied musical knowledge and understanding in the form of *area~*, *polaris~*, and *polygons~*. In addition it has provided a set of three theoretical propositions, termed: augmented materiality, embodiment, and space From this, design patterns for those in the field interested in reproducing or developing similar works, namely: *Designing for Rich AR Experience*, *Consideration of the AR Instrument*, and *Role of the Virtual in the AR Environment*, have been developed below.

9.2 Design Patterns for Sound ARt

In Chapter 4, I outlined the primary vehicle through which to address the key topics and questions of the thesis: the creation and evaluation of sound ARt experiences. These have, in their development and iteration, drawn on a proto-framework of implicit designerly tendencies and patterns that I have found effective - drawing from points of resistance (Section 4.2), and relevant perspectives from the field (Chapter 3). In this section the aim is to outline these patterns in a way that may allow for the creation of similar works of ARt in the future, by members of the experimental music, computational art, and digital humanities fields. The term design pattern here, is borrowed from the field of computer science, where it is taken to describe a set of 'communicating objects and classes that are customized to solve a general design problem in a particular context' (Gamma, 1995). A design pattern thus 'names, abstracts, and identifies the key aspects of a common design structure that make it useful for creating a reusable object-oriented design'. So, while as a method it may not operate completely as it would in its native computer science, to address the outstanding aim of the thesis – namely

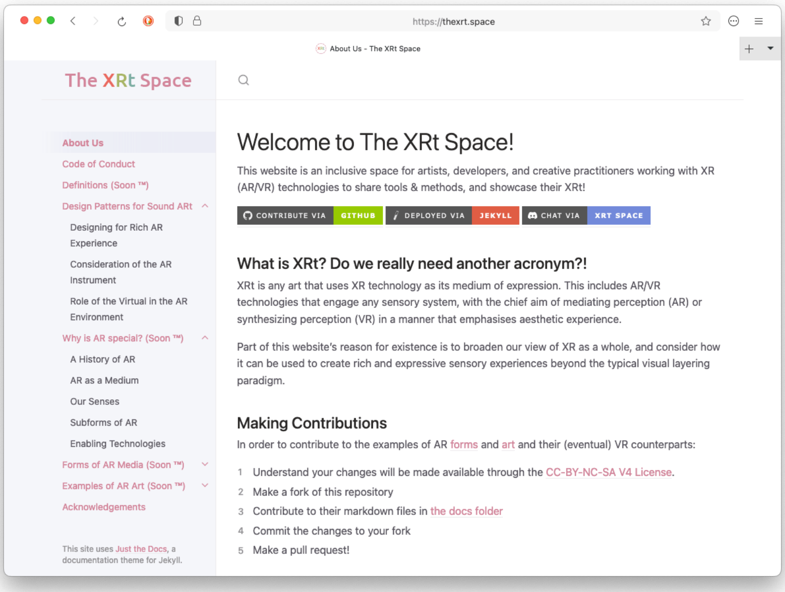


Figure 9.1: The XRt Space website

to contribute to the field of experimental music a guide to sound ARt composition – design patterns do serve to be less rigid than frameworks, more problem-focused than guidelines; whilst inheriting the meaningful organisational structure that comes with an object-oriented design approach. Design patterns are characterised by having four elements:

- The **pattern name** describes the design problem at a higher level of abstraction
- The **problem** describes the specific situation in which you might apply the pattern
- The **solution** describes the relationships between elements of the pattern that aim to solve the problem
- The **consequences** are the results and trade-offs of applying the pattern

These design patterns are therefore subject to iteration, and the latest version can be found on the XRt Space website, a community-editable repository created to host and update them. The principles used to guide the patterns draw on the resistances outlined in Section 4.2, namely taking a DIY approach, decoupling from the ocularcentric and layering paradigms of typical AR experience, and attempting to navigate an inherently consumerist space whilst trying not to contribute to exploitative systems of oppression that uphold it. They are also guided by the theoretical proposals of Chapter 3 and Section 8.4: that participant's and performer's cognitive processes in the experience of AR artworks are embodied, embedded, enacted, and extended, and have the potential to be modulated to extents that offer novel aesthetic experiences of augmented materiality, embodiment, and space. The following sections outline three design patterns, *Designing for Rich AR Experience*, *Consideration of the AR Instrument*, and *Role of the Virtual in the AR Environment*.

9.2.1 Designing for Rich AR Experience

Chapter 3 drew on a number of theoretical propositions, and put forward that AR has the potential to scaffold new modes of performance and expression in the arts and music, furthermore, that from an enactivist approach experience, this would consist in radically modulating the material, embodied, and spatial experience of participants. This is the starting point for ideating and designing an artistic AR experience in the present thesis. This pattern addresses the issue of the typicality of AR experience being simple interactions with visual overlay devices. It approaches experience ideation from a holistic and multisensory, or 'modalities-encompassing' (Schraffenberger, 2018) perspective. Furthermore, the '4Es' of an enactivist approach can be considered as conditions for what could be described as immersive and 'rich experience' (Bilbow et al., 2021). As highlighted in Section 3.4, enactivist principles have been offered as guidelines for the creation of interactive systems in the past; Essl and O'Modhrain (2006), Armstrong (2006), and Hayes (2019) suggest this approach in the design of new musical instruments.

The concept of rich experience also stands in stark contrast to the current direction of corporate XR technologies, where it is being developed to **replace** in-person interactions e.g. by facilitating in-headset 'work from home' VEs such as Meta Horizons. It also stands in contrast with the marketed push towards AR as a tool for driving commerce through targeted advertisements. How as artists and musicians can we avoid the corporate, commercial, ocularcentric, and overlay approach to AR? How can we offset the dystopian hell-scape, painted by designer and film-maker Keiichi Matusda in various film shorts (see Figure 9.2).

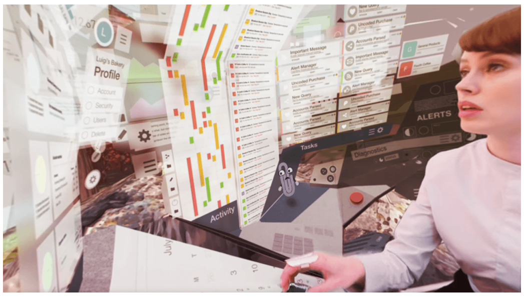
Centre the experience on two or more sensory interactions

Whether it is Dewey's concept of the 'live creature', or the contemporary enactivist's framing of the importance of embodiment, the AR experience ought to be *centred on two or more sensory interactions*. It may include any combination of sensory interaction (display or sensing) types, e.g. visual (vision), auditory (hearing), vestibular (movement and balance), olfactory (smell), gustatory (taste), and somatosensory (touch). This ensures grounding in the importance of the participants agency and sensorimotor structure. Here, the importance of considering the AR experience as an enaction, rather than an abstract internal representation that they are thinking and then acting upon is the important.

(a) *'The Pusher / The Entertainment'* (from Matsuda, 2009)

(b) *'Augmented (hyper)Reality: Domestic Robocop'* (from Matsuda, 2010)

(c) *'HYPER-REALITY'* (from Matsuda, 2016)



(d) *'Merger'* (from Matsuda, 2019)

Figure 9.2: Keiichi Matusda's short films on dystopian AR futures

Invoke a meaningful relationship between the real and virtual

AR's medium specificity, discussed in Section 8.4.2, should be at the forefront of intentional design choices. If AR is unique because of its 'invocation of relationships between real and virtual processes in the axes of spatial, thematic, material and ecological distance', these relationships become a key handle by which artists and musicians can *meaningfully steer experience to achieve aesthetic experiences*. Consider the following:

- Spatial: to what extent should the virtual and real be spatially aligned or even spatially related?
- Thematic: to what extent should the virtual and real be thematically similar, what effect might this have on participants' sense of sensory congruency if distant instead?
- Material: to what extent should the virtual be materially similar to the real environment in which AR brings it into conversation with?
- Ecological: to what extent should the virtual act as part of the real environment, how does this suit the overall narrative intention of the piece?

For the artist or musician, the interest and specificity of AR might lend itself to tending towards the revealing the differences rather than the similarities between the virtual and the real!

Sense	Wearable	Tangible	Situated
Visual	Optical See Through HMD Video See Through HMD Mirrors / Reflectors	Mobile AR	Projection Mapping
Auditory	Hear Through Headphones Mic Through Headphones	Speaker	Wavefield Synthesis Beamforming
Olfactory	Scent Emitter	Scent Emitter	Scent Emitter
Gustatory	Tongue Patch	Edibles	Acoustic Levitation
Somatosensory	Vibrotactile Stimulation Electrical Muscle Stimulation	Vibrotactile Stimulation	3D Printer Mid-Air Haptics

Table 9.1: Potential AR Instruments

Implement an AR subform

In considering the embodied experience of participants, employ Schraffenberger's taxonomy of AR subforms. As discussed in Section 8.4.3, augmented embodiment is achieved through the fact that AR has the potential to radically modulate a participants sense of self, other, and environment. The present thesis has made a clear standpoint on the role of the MIC in biasing the development and conceptualisation of AR towards that of an overlay device or heads-up display. Artists and musicians engaging in AR will already be tending towards the altered and hybridised subforms of AR rather than the purely augmenting; but it is worth mentioning here that significant improvements in the effectiveness of AR in delivering aesthetic experience lies in considering the *process* (see subform) by which perception is mediated by AR.

9.2.2 Consideration of the AR Instrument

When describing the means through which a participant or performer meaningfully interacts or engages in any kind of information transfer in the AR system, it is through what could be termed the AR Instrument. The following categorisation (see Table 9.2.2) may be helpful in considering the plethora of different options available for artists and musicians.

Wearable

Wearable AR Instruments include forms that are worn on the body, including output via head-mounted visual, audio, olfactory and gustatory feedback devices or 'displays', and body-mounted proprioceptive feedback devices

Tangible

Tangible AR Instruments include forms that can explored by holding or touching, such as devices that use conductive fabrics and textiles to track input, and then providing sensory feedback, e.g. vibrotactile stimulation (somatosensory). They can also be any object that can be granted instrumentality by a device that can track it and provide contextually aware, i.e. corresponding, sensory feedback via another device. For example, a wooden cube could be transformed into a Tangible Instrument through real-time image recognition, and specific interactions with it could provide auditory feedback. In this example, the auditory feedback would likely be delivered via a Wearable Instrument that was also processing the real-time image recognition such as an HMD with bone-conduction headphones.

Situated

Situated AR Instruments include forms that are anchored in a real world environment and therefore provide location-specific experiences. Activation is gauged by user enaction, or user presence via infrared camera tracking or proximity of a worn device. Examples of Situated AR Instruments could include an interactive projection mapping with wavefield synthesis providing auditory feedback, and anchored scent emitters providing olfactory feedback

9.2.3 Role of the Virtual in the AR Environment

Allowance for the Real

The use of the game engine Unity, and visual programming languages like Pd / Max MSP have been invaluable in the development of the three outlined sound ARt experiences. Thinking about how they integrate with the real environment of your participant is how AR stays distinct from VR on an interaction level - after all, there must be some reason why as an artist or musician, we decide to work in tandem with, rather than shut off, the real world from our participants! Consider the following:

- What are the sensory boundaries implicit in both the real and virtual space I'm using?
- What different sensory affordances are provided by both the real and virtual environments?
- How might the development of augmented material be influenced by the above factors?
- What real objects are present in the space, is this intentional?

Choosing Experience Size and Complexity

It may be helpful to distinguish between different types of AR 'experience sizes' when first starting out developing sound ARt. For doing this, I developed the following three categorisations. Implying or explicitly stating these boundaries (if it is a public installation) is necessary for building trust and ensuring safety. Intentionally setting boundaries may help in the creative process too.

Snippets describe a small-scale clip-like [1] AR Experiences that occur in the approximate interaction space of 30cm3, e.g. between a users hands. The Snippet itself does not supply a full sensorial experience, instead providing two human-to-sense interactions through its AR subforms.

Scenes describe medium-scale AR Experiences that occur on and around the body, an approximate interaction space of 200cm3. They can be formed from existing Snippets, or created from scratch. They ideally feature more (and higher complexity) human-to-sense interactions, and therefore potentially more interactive relationships between real and virtual elements will be formed.

Spaces describe large-scale AR Experiences, involving multiple participants in a variety of differently sized interaction spaces in a room. For example, augmented hand / body interaction with the environment and other users, and multiple of zones of interaction in different sections of the space. Spaces provide fully multisensory immersive experiences, by making use of a combination of different sensory modalities and AR subforms.

9.3 Future Work

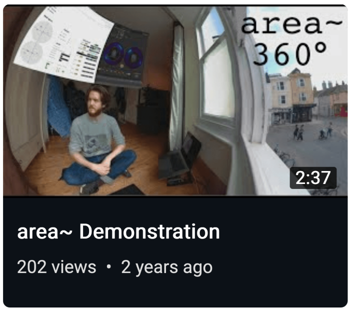
It is my hope to carry on developing expressive tools for musical creativity long into the future, and these will be located on on my website. In *Performing polygons~*, I remarked on the work that was outstanding in developing a sound ARt performance practice. It is my hope in the near future, to develop a set of tools for artists and musicians interested in collective forms of AR headset expression, with a project entitled CoMuSe: Collective Musical Sensehacking. This will explore 'multiplayer' or ensemble sound ARt performances.

[1] Similar in scale to the video-clip, sound-clip, clipart, and now app-clip, however conceptually different in that Snippets are not a miniaturised 'extracts' or 'segments' of a larger experience

APPENDICES

A area~ Archive

A.1 area~ Related Media

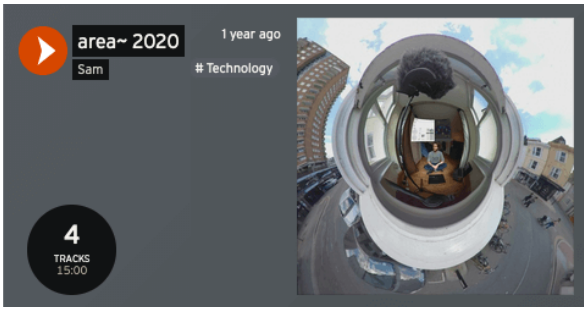


youtu.be/SPd-f2EXuIQ

youtu.be/rhtrAERxFQQ

youtu.be/iZRcBhC13_4

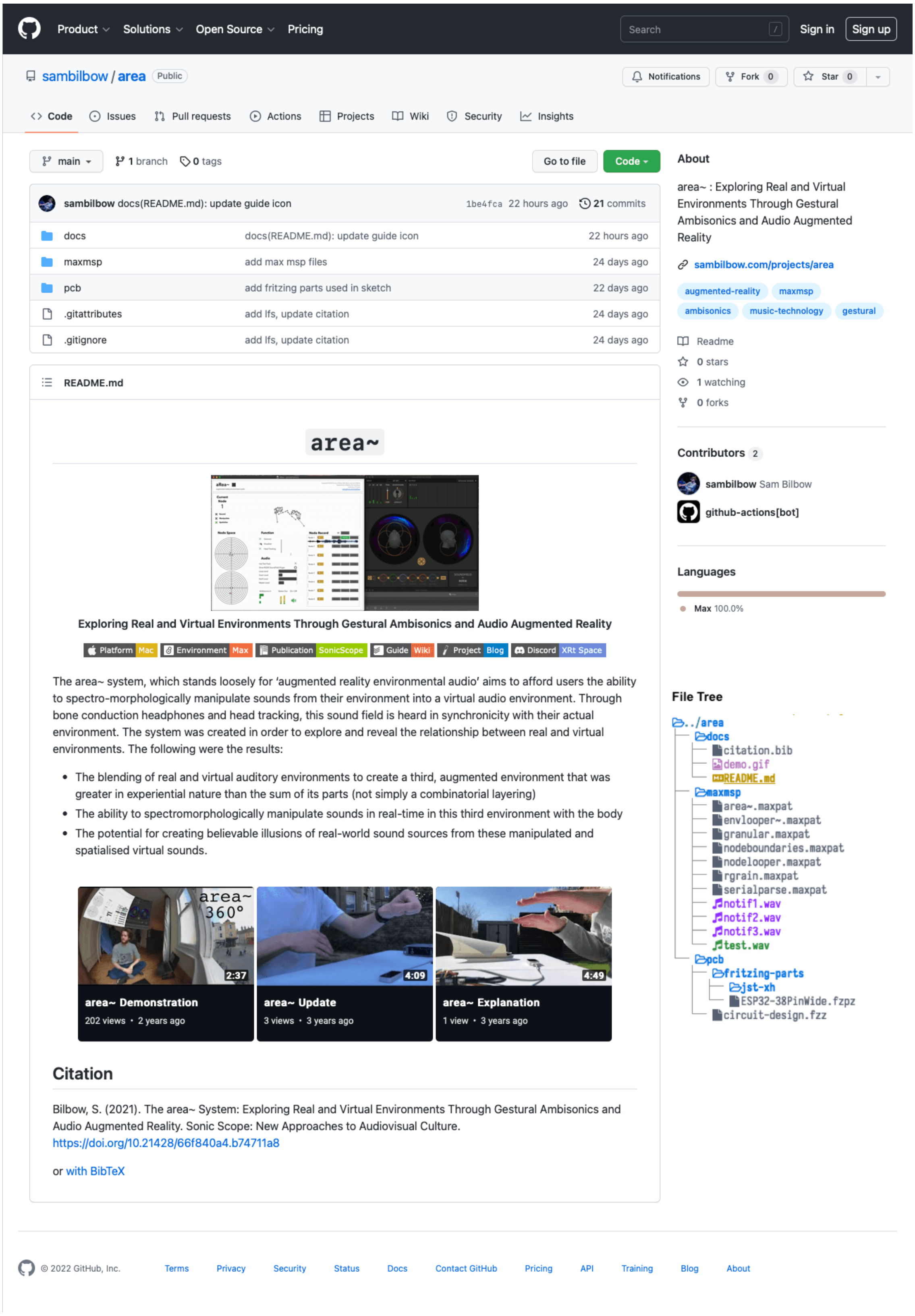
area~ Video Recordings



soundcloud.com/sambilbow/sets/area2020

area~ Binaural Audio Recordings

A.2 area~ Code Repository



github.com/sambilbow/area
area~ on GitHub with file tree

A.3 area~ Blog Contents

this is a 360 / ambisonic video. that means that as long as you are viewing on desktop, you can drag the video around in 3 dimensions and hear the sound pan around you. wear headphones for best results.

area~ (May, 2020)

project paper: sonicscope issue two journal article

Summary

The area~ system, which stands loosely for 'augmented reality environmental audio' aims to afford users the ability to spectromorphologically (defined by Smalley to concern spatial, temporal and textural qualities of sound (1997)) manipulate sounds from their environment into a virtual audio environment. Through bone conduction headphones and head tracking, this sound field is heard in synchronicity with their actual environment. The system was created in order to explore and reveal the relationship between real and virtual environments.

Through an autobiographical design study, these experiences are discussed in relation to the research question: "How can we better understand relationships between virtual and real environments through gesture and virtually placed audio augmented reality objects?" This hypothesis study proposes that new aesthetic experiences can result from the system and are waiting to be tested through user studies. The adoption of the North Star open-source AR head-mounted-display could expand the possibilities of the area~ system by reducing the need to be tethered to a laptop and table for hand gesture input.

Overall, the results from ABD have shown that area~ is an effective tool for examining the combinatorial relationship between real and virtual environments. Despite the systems hardware setup needing to be worked on to allow for quicker start up and more accurate head tracking, it has provided me with novel aesthetic experience through:

- The blending of real and virtual auditory environments to create a third, augmented environment that was

greater in experiential nature than the sum of its parts (not simply a combinatorial layering)

- The ability to spectromorphologically manipulate sounds in real-time in this third environment with the body

- The potential for creating believable illusions of real-world sound sources from these manipulated and spatialised virtual sounds.

Technologies

The three technologies used in area~, are gestural hand tracking, rotational head tracking, and ambisonics. The gestural hand tracker used in the system is a Leap Motion LM-010 Controller, a USB infrared camera device that provides location and orientation data output of individual finger joints (and therefore hands) when they are presented above the device. The Leap Motion Controller (LMC) has been adopted in a multitude of settings such as being mounted on VR headsets (Leap Motion 2016), and converting hand gestures to MIDI (Leap Motion 2017). More recently, UltraLeap are investigating the use of this same technology with gesture-based public information screens to help combat the "hygiene risks of touch screens" (2020).

Rotational head tracking is achieved via an inertial measurement unit (IMU). This small and inexpensive component provides orientational data output at 20 times a second. When affixed to the head via a headset or headphones, it is a relatively easy and cheap way of implementing head tracking into the system.

Ambisonics is an audio format that allows for full-spherical audio capture and playback (Gerzon 1973). There are four recorded channels (referred to as A-Format) that unlike regular mono, stereo, or surround sound formats, contain no information about the speakers it is delivering the signal to. Rather, these channels can be encoded in such a way as to describe a three-dimensional field of sound referred to as B-Format. B-Format can be decoded through "virtual microphones", any number of which can be placed within this three-dimensional sound field to provide standard channel outputs.

For example, in area~, I have used a RØDE Soundfield NTSF-1 microphone array comprised of 4 microphones. The A-Format output is encoded to B-Format by an audio plugin. A software library I have configured, further decodes the B-Format to two responsive, binaural, virtual audio output channels. This all occurs in real-time; and as the user moves their head, the microphones inside the three-dimensional sound field rotate proportionally, providing realistic changes to what is heard.

Experience

The recording or 'sampling' stage is initiated by making a left-hand grab above the LMC, the longer lasting the grab, the longer the portion of audio from the ambisonic palette is sampled. The three-dimensional coordinates of the hand above the LMC correlates with the location of audio recorded (this is achieved by mapping the hand coordinates to a virtual microphone inside the ambisonic palette), essentially allowing the user to record sounds around their person in three dimensions. Upon letting go of the grab gesture, the sample plays on repeat (using the karma~ Library (Constanzo 2015)) through the bone conduction headphones, thus setting up the session's virtual audio environment.

The manipulation stage is automatically initiated after the ending of the previous grab gesture and uses translational (x, y, z) and rotational (roll, pitch) values from both hands when above the LMC. There are two audio effects being manipulated, with parameters from these effects mapped in different ways to the translation and rotation of the user's hands. When the user decides to end manipulating the sample, they can do so by performing a grab with both hands. Once this happens, the band-pass filter and granular synthesis parameters are frozen for that sample.

The spatialise stage begins once the manipulation stage is ended by the user. The three-dimensional space above the LMC is mapped to the virtual audio environment, in which the user is currently listening to the sample that they have recorded. The user can use their right hand to move the sample around the virtual audio environment. For an example of the effect this has, moving the hand between the two extremes of the x-axis (left to right) results in hearing the sample move from ear to ear. The spatialise stage is ended by grabbing with the right hand.

Once the spatialise stage has ended, the user has the option to repeat the process 7 more times, allowing for the creation of a virtual audio environment comprised of up to 8 spatialised audio samples, or what I refer to as nodes. Below are some examples of these virtual audio environments.

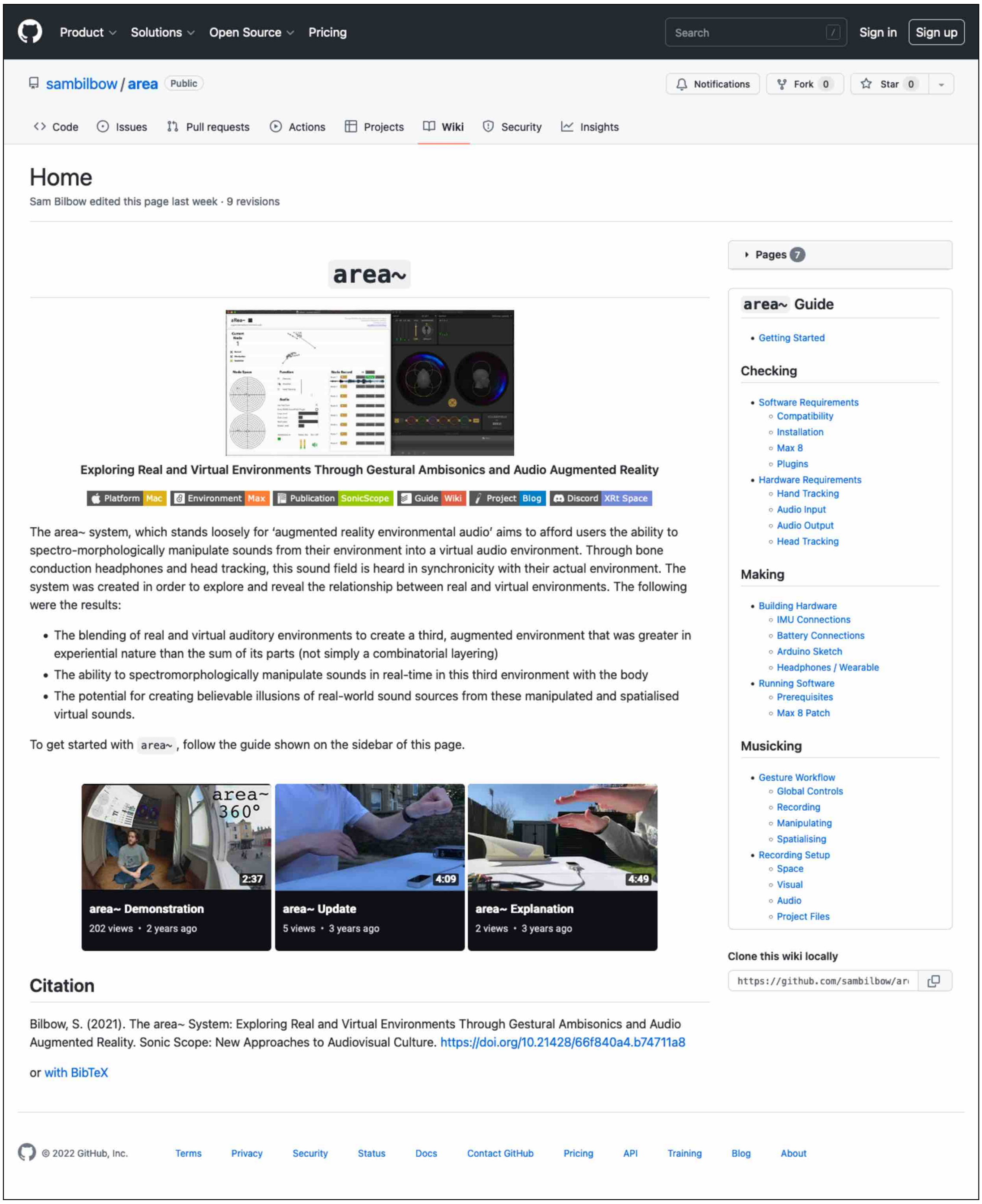
virtual audio environment 1 (inside) SOUNDCLOUD

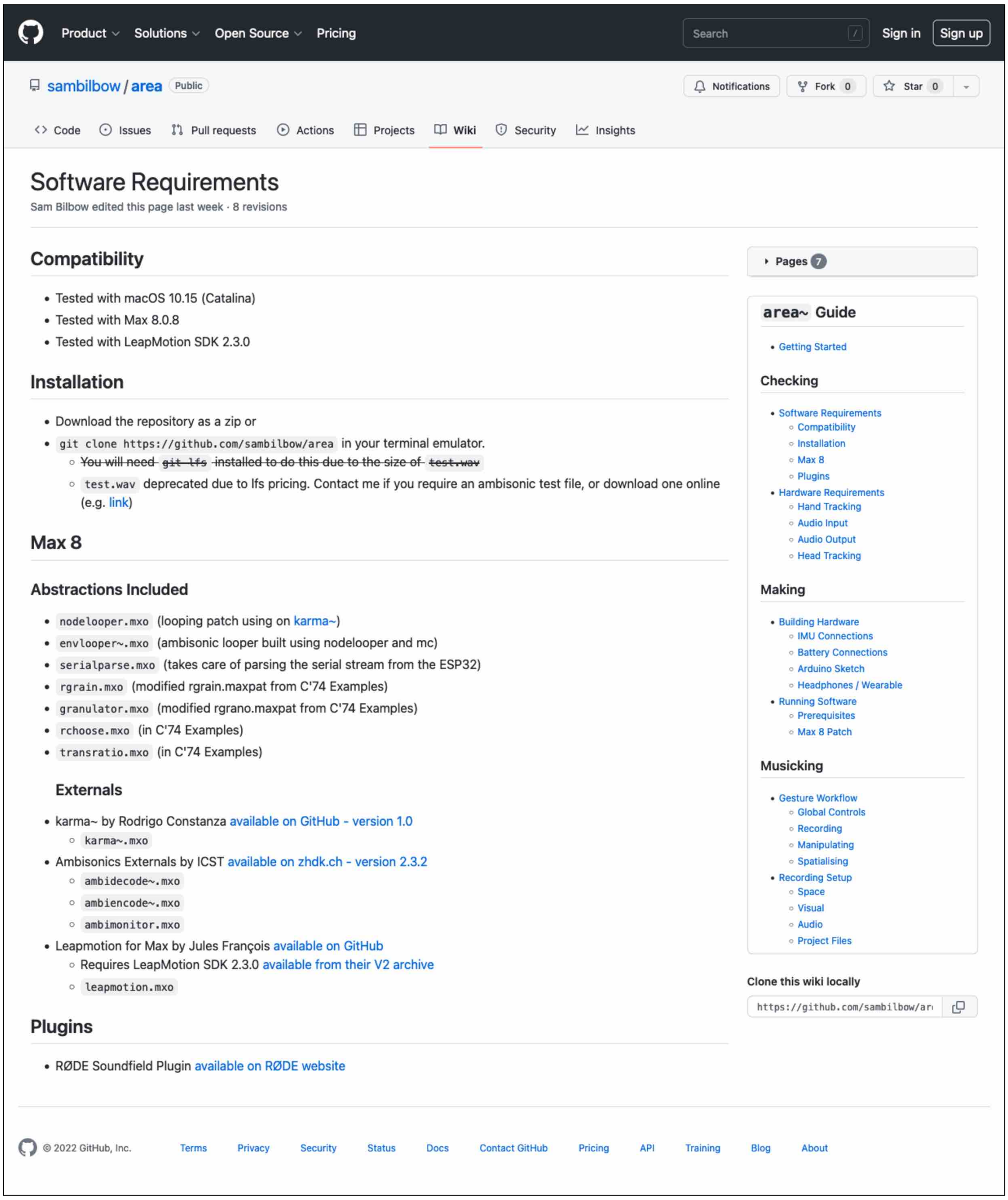
virtual audio environment 2 (birds) SOUNDCLOUD

virtual audio environment 3 (meeting) SOUNDCLOUD

virtual audio environment 4 (outside) SOUNDCLOUD

A.4 area~ Project Guide





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Software Requirements

Sam Bilbow edited this page last week · 8 revisions

Compatibility

- Tested with macOS 10.15 (Catalina)
- Tested with Max 8.0.8
- Tested with LeapMotion SDK 2.3.0

Installation

- Download the repository as a zip or
- `git clone https://github.com/sambilbow/area` in your terminal emulator.
  - ~~You will need `git-lfs` installed to do this due to the size of `test.wav`~~
  - `test.wav` deprecated due to lfs pricing. Contact me if you require an ambisonic test file, or download one online (e.g. link)

Max 8

Abstractions Included

- `nodelooper.mxo` (looping patch using on karma~)
- `envlooper~.mxo` (ambisonic looper built using nodelooper and mc)
- `serialparse.mxo` (takes care of parsing the serial stream from the ESP32)
- `rgrain.mxo` (modified rgrain.maxpat from C'74 Examples)
- `granulator.mxo` (modified rgrano.maxpat from C'74 Examples)
- `rchoose.mxo` (in C'74 Examples)
- `transratio.mxo` (in C'74 Examples)

Externals

- karma~ by Rodrigo Constanza available on GitHub - version 1.0
  - `karma~.mxo`
- Ambisonics Externals by ICST available on zhdk.ch - version 2.3.2
  - `ambidecode~.mxo`
  - `ambiencode~.mxo`
  - `ambimonitor.mxo`
- Leapmotion for Max by Jules François available on GitHub
  - Requires LeapMotion SDK 2.3.0 available from their V2 archive
  - `leapmotion.mxo`

Plugins

- RØDE Soundfield Plugin available on RØDE website

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  - Headphones / Wearable
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  - Max 8 Patch

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  - Global Controls
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https://github.com/sambilbow/ar

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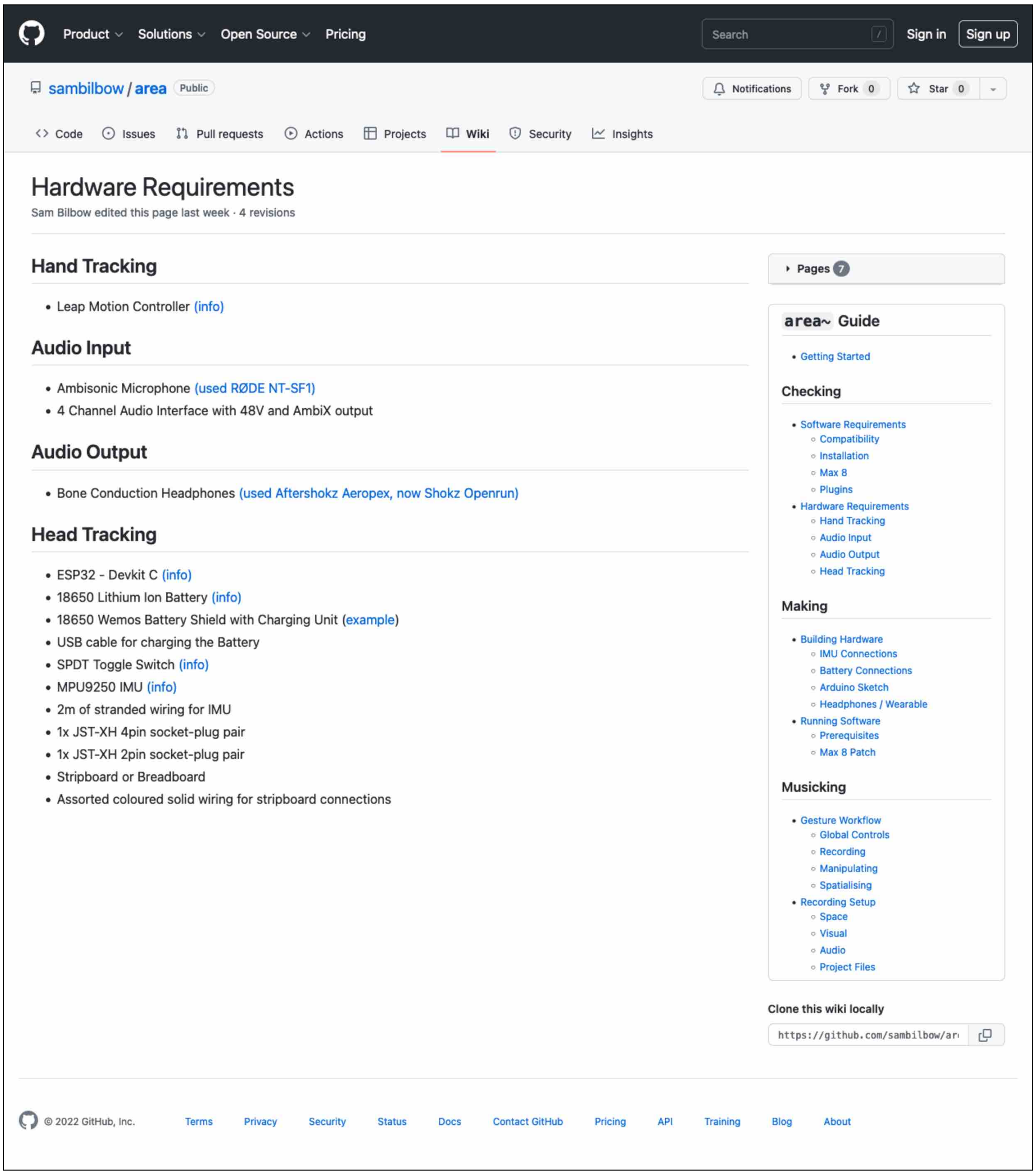

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Hardware Requirements

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Hand Tracking

- Leap Motion Controller (info)

Audio Input

- Ambisonic Microphone (used RØDE NT-SF1)
- 4 Channel Audio Interface with 48V and AmbiX output

Audio Output

- Bone Conduction Headphones (used Aftershokz Aeropex, now Shokz Openrun)

Head Tracking

- ESP32 - Devkit C (info)
- 18650 Lithium Ion Battery (info)
- 18650 Wemos Battery Shield with Charging Unit (example)
- USB cable for charging the Battery
- SPDT Toggle Switch (info)
- MPU9250 IMU (info)
- 2m of stranded wiring for IMU
- 1x JST-XH 4pin socket-plug pair
- 1x JST-XH 2pin socket-plug pair
- Stripboard or Breadboard
- Assorted coloured solid wiring for stripboard connections

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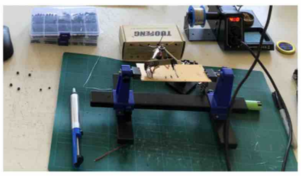
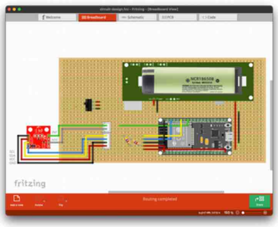
Building Hardware

Sam Bilbow edited this page last week · 6 revisions

IMU Connections

1. Form 2 metres of cabling, I heatshrunk the cables together, you'll need 6 in total.
2. Crimp JST-XH plugs onto the cables. I chose to bundle the VCC, GND, SCL, SCA into a 4 pin connector, and the AD0 and INT into a 2 pin connector.
3. Solder the cabling onto the IMU, taking care to note down which cable is connected to each pin
4. Solder the JST-XH corresponding sockets to your stripboard.
5. Solder resistor connectors
6. Plug in the IMU cables.
7. Solder solid core cabling from the strips connected to each JST-XH socket pin, via resistors if specified, to the following ESP32 pins.

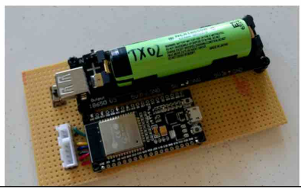
IMU Pin	ESP32 Pin
VCC	3V3
GND	GND
SCL/SCLK	GPIO22 via 4.7 kΩ to 3V3
SDA/SDI	GPIO21 via 4.7 kΩ to 3V3
AD0/SDO	None
INT	GPIO19

Soldering in Progress	Fritzing Schematic from /area/pcb/
	

Battery Connections

1. Connect the battery shield to the ESP32
2. Use an SPDT toggle switch if you wish to be able to toggle the power, and conserve charge when not using
3. Put the 18650 cell in to the shield

18650 Shield	ESP32 Pin
5V	5V
GND	GND



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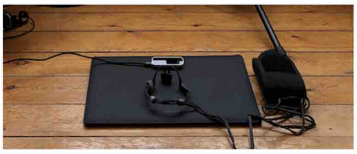
Arduino Sketch

`under (re)construction`

1. Due to data corruption, the actual sketch has been lost. It drew on this sketch by Kris Winer, that uses open source sensor fusion algorithms to increase the stability and accuracy of the sensor. Adapting the sketch involved removing redundant measurements from the serial print calls. At a later date I may have time to create the sketch again.
2. The only data needed from the IMU is the head rotation. This can tested by sending all three rotation values via Serial, rotating your head whilst the sensor is attached to the bone condudction headphones, and selecting the measurement which corresponds with the axis that experiences the largest delta.
3. The sketch used the onboard Bluetooth capabilities of the ESP32 to send the serial data via BT.
4. Flash the ESP32 via USB (you will require your ESP32's Arduino Library, as well as esptool installed).

Headphones / Wearable

1. Place circuit inside a wearable pouch - I used a belt pouch for a PDA I found online
2. Orient circuit so that USB B Micro on the Battery Shield is accessible for charging.
3. Connect the IMU to the bone conduction headphones. I did this via velcro, so that it was somewhat adjustable while using.



Running Software

Sam Bilbow edited this page last week · 4 revisions

Prerequisites

1. You have all the Software Requirements
2. The ambisonic microphone is plugged in, powered by 48V and selected in Max's audio options
3. The wearable IMU / bone conduction headphones are on, connected to the host computer, and transmitting data.
4. The bone conduction headphones are selected as the audio output in Max's audio options

Max 8 patch

1. Open `area~.maxpat` in Max 8
2. Connect to the appropriate serial device
   i. Leave presenter view (cmd-option-e)
   ii. Open `[p serial]`
   iii. Enter edit mode (cmd-e)
   iv. Change `[serial b 115200]` to reflect your serial device's index
   v. Leave edit mode (cmd-e)
   vi. Close `[p serial]`
   vii. Enter presenter view (cmd-option-e)
3. Set up the patch audio settings
   i. Turn on the Stereo Out `[ezdac~]`
   ii. Loop Level `[slider]`
   iii. Grain Level `[slider]`
   iv. Notification Level `[slider]`
   v. Main Level `[slider]`
   vi. Check the RØDE Plugin to ensure signal from the microphone is being received
   vii. (optional) If not using a microphone, place an ambisonic file called `test.wav` in project root folder, and toggle on `Use Test Track [x]`
4. Turn on the function toggles
   i. `[x] Gestures`
   ii. `[x] Visualiser` (optional)
   iii. `[x] Head Tracking`
      a. The `ambimonitor` on the left side of the patch should now show two points rotating as your head moves

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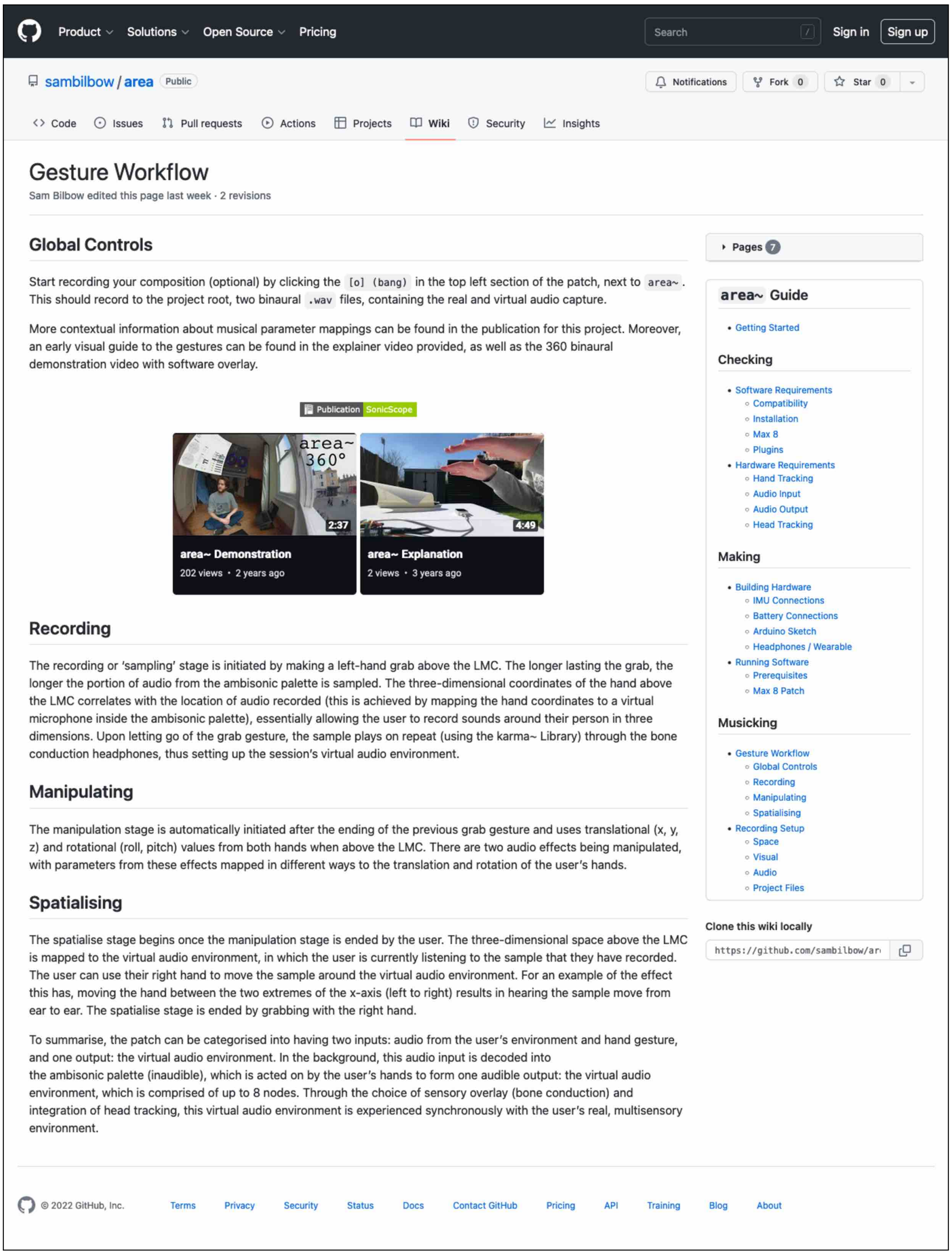

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Gesture Workflow

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Global Controls

Start recording your composition (optional) by clicking the `[o] (bang)` in the top left section of the patch, next to `area~`. This should record to the project root, two binaural `.wav` files, containing the real and virtual audio capture.

More contextual information about musical parameter mappings can be found in the publication for this project. Moreover, an early visual guide to the gestures can be found in the explainer video provided, as well as the 360 binaural demonstration video with software overlay.

Publication SonicScope

area~ 360° 2:37 area~ Demonstration 202 views • 2 years ago

4:49 area~ Explanation 2 views • 3 years ago

Recording

The recording or 'sampling' stage is initiated by making a left-hand grab above the LMC. The longer lasting the grab, the longer the portion of audio from the ambisonic palette is sampled. The three-dimensional coordinates of the hand above the LMC correlates with the location of audio recorded (this is achieved by mapping the hand coordinates to a virtual microphone inside the ambisonic palette), essentially allowing the user to record sounds around their person in three dimensions. Upon letting go of the grab gesture, the sample plays on repeat (using the karma~ Library) through the bone conduction headphones, thus setting up the session's virtual audio environment.

Manipulating

The manipulation stage is automatically initiated after the ending of the previous grab gesture and uses translational (x, y, z) and rotational (roll, pitch) values from both hands when above the LMC. There are two audio effects being manipulated, with parameters from these effects mapped in different ways to the translation and rotation of the user's hands.

Spatialising

The spatialise stage begins once the manipulation stage is ended by the user. The three-dimensional space above the LMC is mapped to the virtual audio environment, in which the user is currently listening to the sample that they have recorded. The user can use their right hand to move the sample around the virtual audio environment. For an example of the effect this has, moving the hand between the two extremes of the x-axis (left to right) results in hearing the sample move from ear to ear. The spatialise stage is ended by grabbing with the right hand.

To summarise, the patch can be categorised into having two inputs: audio from the user's environment and hand gesture, and one output: the virtual audio environment. In the background, this audio input is decoded into the ambisonic palette (inaudible), which is acted on by the user's hands to form one audible output: the virtual audio environment, which is comprised of up to 8 nodes. Through the choice of sensory overlay (bone conduction) and integration of head tracking, this virtual audio environment is experienced synchronously with the user's real, multisensory environment.

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Recording Setup

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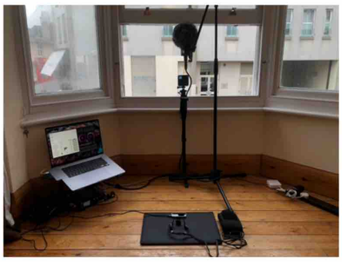

Space

- Choose a space with an interesting sound palette!
- Monitor the audio for a while, get to know the sounds. Perhaps a deep listening exercise?
- I found it best to sit down, you're tethered by the length of your LMC USB cable anyway

Visual

- I found that the recordings of compositions worked really well with an accompanying 360 video, I used a GoPro for this. I used GoPros tool to bounce down the two sides of 360 video into an equirectangular video.
- I also took a screen recording of the patch whilst composing, using QuickTime Player
- These were composited in Adobe Premiere Pro, with the screen view acting as a 'picture-in-picture'

Audio

- The patch outputs (if enabled) two 4-channel B-Format `.wav` files to your user directory: `~/`, `realEnv.wav` and `virtualEnv.wav` containing the real and virtual audio capture from the patch.
- I added these to the Premiere Pro project as ambisonic audio
- I then mixed down the project to equirectangular, with ambisonic audio, for YouTube 360.

Project Files

Sources

- 360 footage `.mov` (converted from GoPro GBACK and GFRONT `.mp4` files)
- Screen Recording of Max 8 `.mov`
- B-Format Microphone Capture `realEnv.wav`
- B-Format Max 8 Capture `virtualEnv.wav`

Output

- Equirectangular 360 / Ambisonic video `.mp4`

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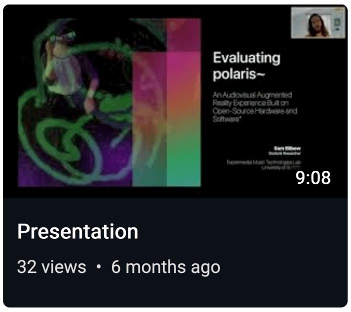
B polaris~ Archive

B.1 polaris~ Related Media



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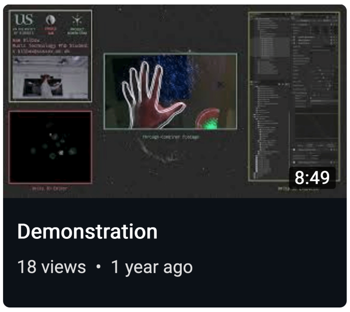

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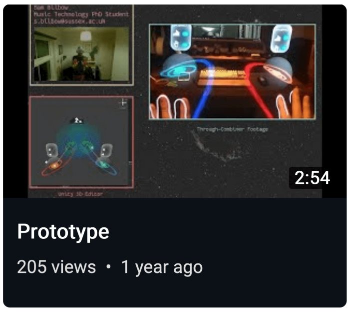

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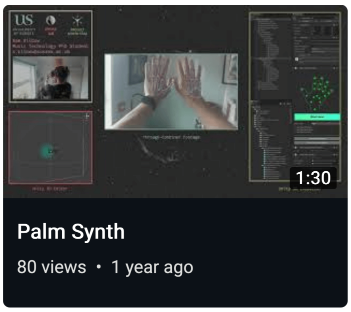

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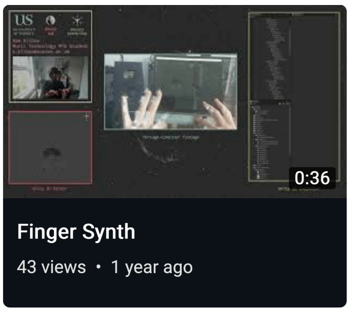

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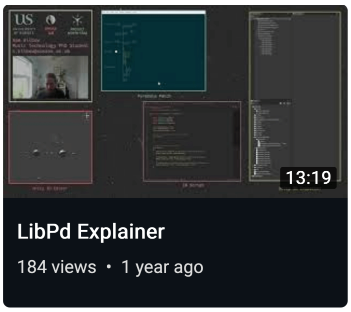

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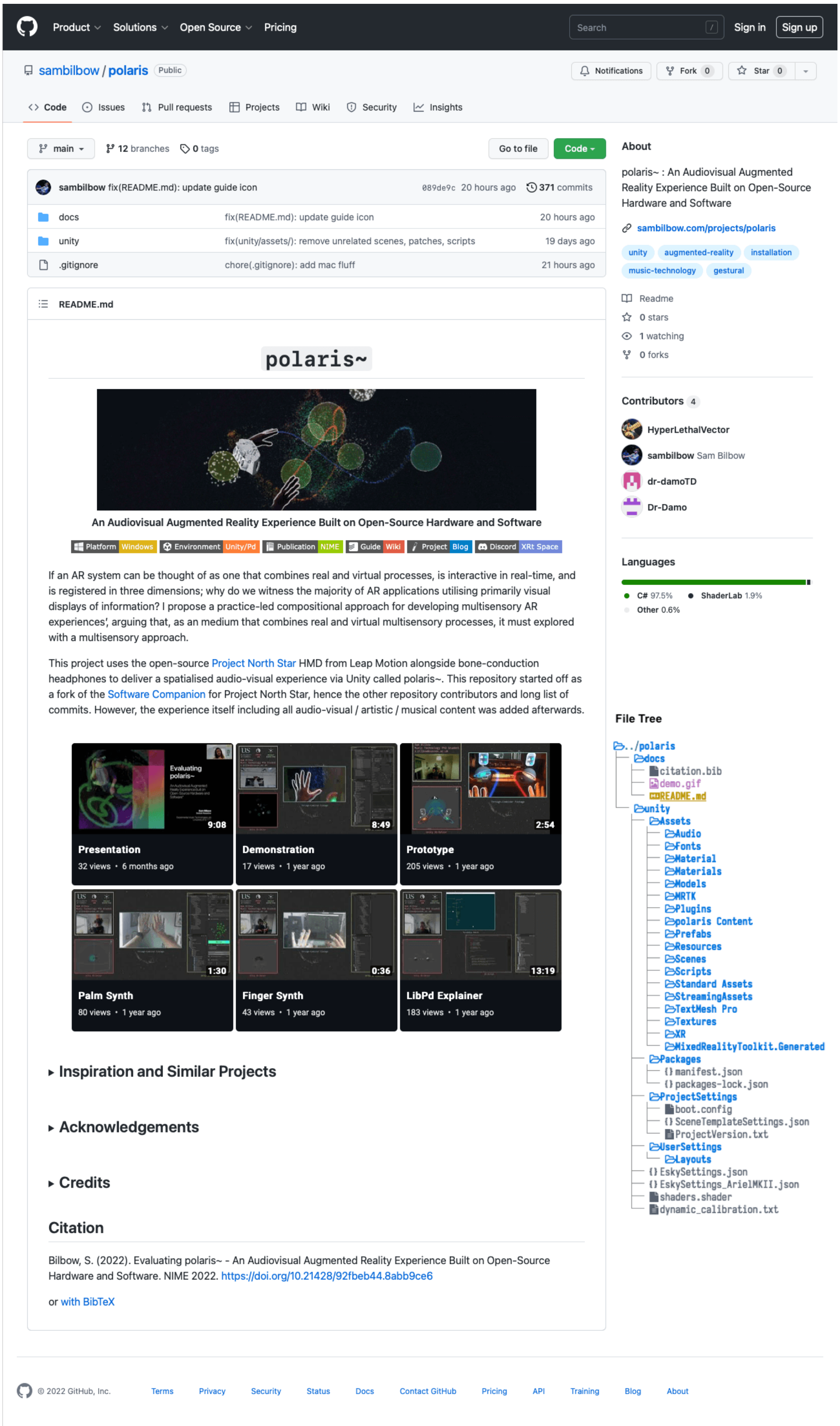
polaris~ Video Recordings

B.2 polaris~ Code Repository



github.com/sambilbow/polaris
polaris~ on GitHub with file tree

B.3 polaris~ Blog Contents

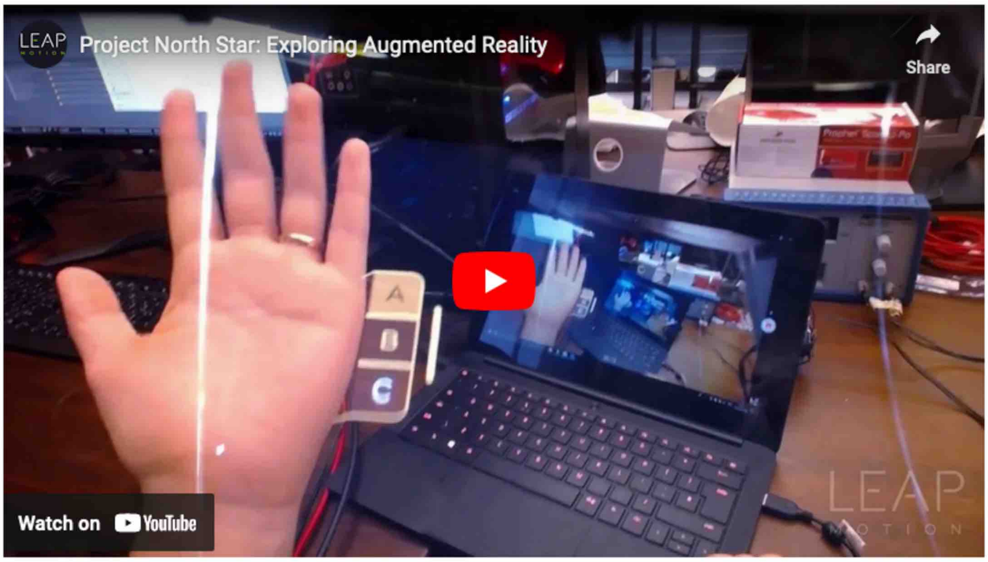
B.3.1 Summary

Summary

If an AR system can be thought of as one that combines real and virtual processes, is interactive in real-time, and is registered in three dimensions; why do we witness the majority of AR applications utilising primarily visual displays of information? I propose a practice-led compositional approach for developing 'Multisensory Augmented Reality (MSAR) Experiences', arguing that, as an medium that combines real and virtual multisensory processes, it must explored with a multisensory approach.

This project (polaris~) uses the open-souce Project North Star HMD from Leap Motion, whose general documentation can be found in the resources section. I am using the Project Esky MRTK Unity Implementation for building the software in Unity3D, which is developed by Damien Rompapas (massive thank you for all the hours you have spent helping me with errors and bugs).

This page outlines my use of the system which started around June of 2020 and is ongoing. To clarify, the original design has been open sourced by Leap Motion since 2018, but there have been a fair few community revisions and updates to the design (see more here). This page documents the development of the CombineReality Deck X version of the Project North Star HMD. CombineReality is run by Noah Zerkin, who has provided countless support to my own project, so thanks Noah! He's also pretty much the only inexpensive parts sourcer of the electrical bits needed for the headset.



LeapMotion video from 2018 showcasing through-combiner footage of the robust hand tracking in North Star

B.3.2 Inspiration & Rationale

Inspiration & Rationale (May - July 2020)

During the development of the pilot study for my PhD: the area~ system, I came across the open-source Project North Star AR headset. It had a very clear set of advantages detailed below:

Visual Display

- 2K resolution per-eye OLED displays

Tracking

- Hand Tracking (Ultraleap Stereo IR 170)
- 6DoF Body Tracking (Intel T261)

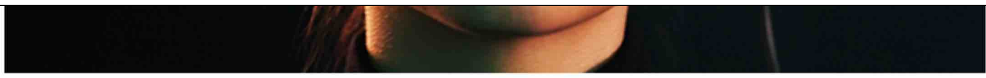
Software

- Unity Implementation (Project Esky)

Miscellaneous

- Community of makers (>2000 people)
- Open-sourced design - ability to expand to other sensory modalities
- .stl files for 3D Printing
- Cheap in comparison to Microsoft HL2 and Magic Leap ML-1

I therefore thought it would be a good platform to design my further studies with. Either in conjunction with wireless bone conduction headphones, or via desigining, 3D printing, and implementing a bone conduction solution for the headset.



B.3.3 Hardware

Hardware (July - December 2020)

Shopping List

£300 CombineReality Deck X Kit A (buy Kit B if you don't have access to a 3d printer for +£100)

£110 Intel T261

£100 Ultraleap Stereo IR 170 (or use a Leap Motion Controller if you already have one)

£510 Total Cost (£610 if you don't have access to a 3d printer)

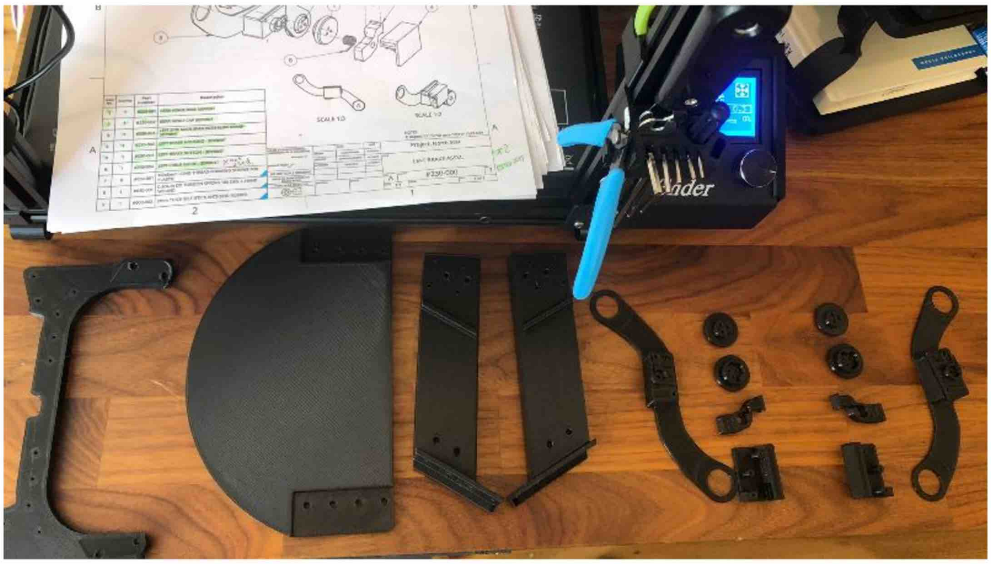
3D Printing

I started printing the parts (which are now available here) between July and September,

Electricals and Sensors

Building the headset involves assembling the electrical components and the sensors into the 3D printed parts. For the Deck X, these electrical components are:

- Intel T261 (6DOF Sensor)
- Ultraleap Stereo IR 170 (Hand Sensor)
- Display Board (The board which provides power to the two displays, and receives their signal via a mini Display Port cable)
- CombineReality Integrator (CR's solution to reduce cables: in older iterations of the HMD, you needed a USB cable to power the display board as well as each of the sensors. This amounted to four cables. The Integrator 'integrates' everything with one unidirectional USB C - A cable.
  - It contains a USB C hub to power and relay sensor data from two USB 3.1 and one USB 2.0 connectors
  - Sends power to the Display Board via a connector and capacitor board.
  - Contains a 3GB on-board flash drive
  - Features an arduino-compoatible microcontroller (allows further sensors, and integrates the D-Pad on the lid)
  - Power for a fan to cool the T261 and all other inner components
- Lid D-Pad (CR's 6 button solution to allow hassle-free calibration and easy resetting)
- Capacitor Board (to power the Display Board from the Integrator)
- Screens (two screens that add up to a 2880x1600 120Hz display extension to your computer)



Some photos of my 3D printing process. Around January I updated to the Ultraleap Stereo IR 170 hand tracker from the Leap Motion Controller, which offers higher field-of-view. This required a reprint of the main optics bracket which is why the headset might look different in some pictures further along the process

Assembly

The full assembly guide for the CombineReality Deck X version of the North Star HMD is available here.

B.3.4 Software: Calibration

Software: Calibration (December - May 2021)

Initiation

Originally, my system was very temperatmental. After much deliberation, I realised I must have shorted some part of my integrator. After replacing it, everything is plug and play. Luckily I was mainly working on written parts of my PhD during this period of time.

For best results I plug in the USB, and then the DP cable into my computer, and unplug them in the opposite order.

Software Development Kits Needed

Intel Realsense SDK (enables head tracking)

- Latest Intel RealSense SDK 2.0 - you're looking for an asset file like "Intel.RealSense.SDK-WIN10-2.47.0.3309.exe"

Ultraleap Gemini SDK (enables hand tracking)

- Leap Developer Kit 5.0.0-preview+52386
- Leap Developer Kit 4.0.0+52238 - need to rollback to this driver to run Leap Motion example demonstrations such as Paint and Cubes

Optical Calibration

Calibrating the headset is necessary due to the large amount of small variables between headsets this stage. Lets have a look at some things that might not be the same for everyone:

- 3D Filament Type (material and layer height)
- 3D Printer Tolerances (how accurate the print is +/- mm)
- Resultant Inter-Hardware Position (the above two factors might result in minute differences in position between hardware components)

For this reason, it is commonplace to "calibrate" your headset through software, by creating a file which contains information about the various positions of hardware (I believe mainly the screens). This already sounds very difficult, so how does it work?

Historically, there are two different types of calibration, 3D and 2D. 3D came first, and is therefore (frustratingly) sometimes referred to as V1 calibration. 2D came second, and is referred to as V2 calibration. See the differences here.

- 3D Calibration (V1) requires the use of two extra cameras and is therefore more expensive and a longer process. It was necessary to do this before the North Star had a 6DoF sensor with a dual-camera at its disposal

- 2D Calibration (V2) uses the dual-camera in the 6DoF sensor (Intel T261), and is therefore cheaper and quicker.

Historical 2D (V2) Calibration Stand vs New T26x Hybrid Calibrator

2D (V2) calibration used to require placing the headset on a special calibration stand, taking the T261 and anchoring it where the eyes would sit behind the headset. These are the first photos in the slideshow.

Thanks to the new T26x Hybrid Calibrator, the stand is no longer necessary, as is shown in the last two photos

Calibration is fairly simple and requires running premade python scripts. Instructions are here (I created a custom anaconda virtual environment (venv) to install the packages and run the calibration scripts from this venv). The output are four number arrays, which can later be used in Unity to make sure that each eye receives calibrated visuals from the screens. I keep these arrays in a sacred folder called "CALIBRATIONS DO NOT TOUCH"

B.3.5 Software: Running Demos

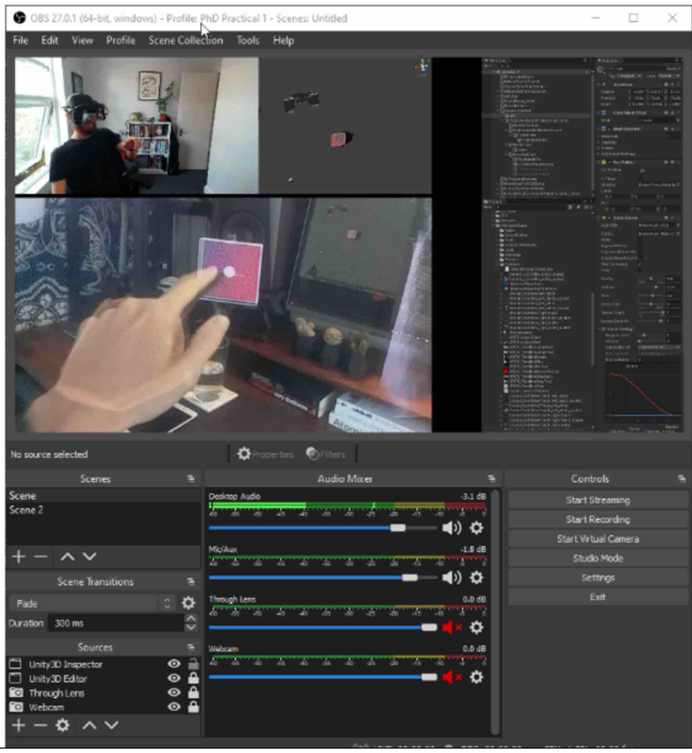
Software: Running Demos (May - July 2021)

Through-Combiner Recording

In July I added a camera to the headset, to be specific, I have a Raspberry Pi Zero, taking power over USB 2 ribbon cable from the CombineReality Integrator, connected to a ZeroCam (small camera), placed just to the right of the left screen on the headset. This results in the camera being in front of my left eye. Despite making it harder to see objects, for documentation and archival purposes, the camera has been a great addition. Following these instructions, the camera shows up as a standard USB camera through the headset's USB 3 cable. This cable to the PC is now not only powering and transferring data to and from the sensors and displays, but now also the new camera, all through one cable!

Raspberry Pi Zero + ZeroCam Through-Combiner Setup

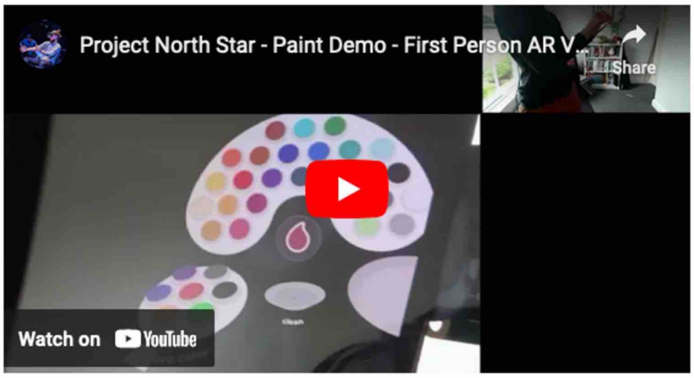
In order to take these videos, I use OBS to composite my webcam, specific portions of my screen (during Unity Demos), as well as the through-combiner camera I have set up, and later on, binaural audio. Overall, whilst it looks and feels hacked together, and could probably do with a 3D printed enclosure, the system works perfectly well for documenting the experience of wearing the headset.



My OBS camera/screen/audio compositing setup

Paint & Cubes

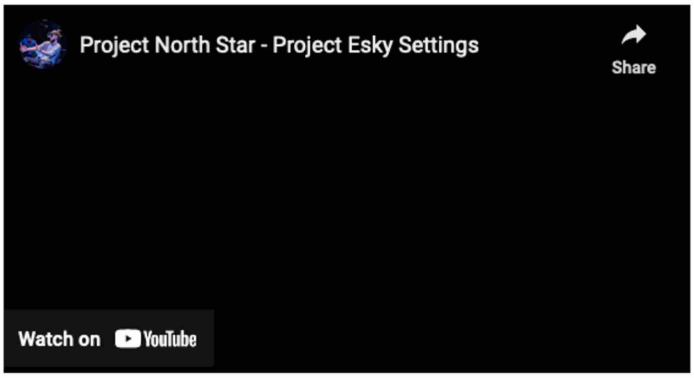
Now that the headset is built, the SDKs are installed, and I have a 2D optical calibration, it was time to run a few demos. The first video above shows this original Unity demo from Leap Motion. As mentioned in the calibration page , if you want to run this yourself, you need to be on the multi-device support SDK.

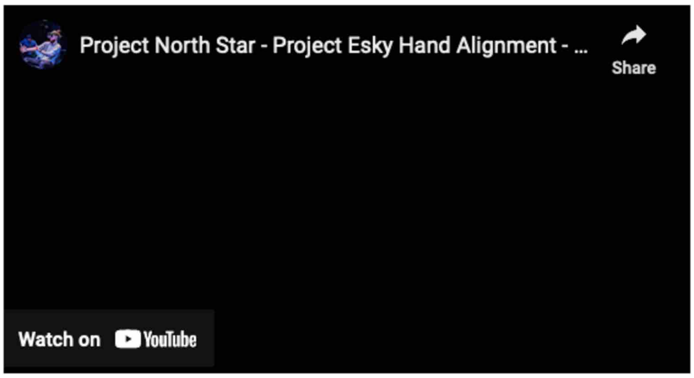


Project Esky

Project Esky is a open-source software platform apable of high fidelity natural hand-interactions with virtual content, high field of view, and spatial mapping for environment interactions. This is the software framework by which I am creating my AR experiences in Unity. It is developed by Damien Rompapas, who has helped a lot in helping my project run smoother. Esky allows the North Star to be emulated as a Windows Mixed Reality Headset, meaning that you can use the Microsoft Mixed Reality Toolkit in Unity3D for desigining interactions (like the Microsoft Hololens 2 does)

There are a couple of important steps I had to go through before I could use Esky properly, importing calibration, setting up display settings, and aligning my hands. The third video covers importing my optical calbration into Project Esky, and the fourth video covers hand alignment, which makes sure that your virtual and real hands are aligned.





From here on, when working in Unity 3D, it is assumed that I am referring to the Project Esky Unity Implementation

B.3.6 Software: Planning Musical AR Instruments

Software: Planning Musical AR Instruments (July - August 2021)

Current state of the ARt

At this stage, I have a working visual AR headset... what about audio? As mentioned in the inspiration for this project I am using wireless bone conduction headphones, after trialling their use for audio AR in the area~ project. I use these because they serve as an aural equivalent to the method of visual mediation being used with the headset ('see-through' = 'hear-through'), that is to say, just as the headset does not occlude the sight of real physical objects in the participant's environment by using a half-mirror to combine virtual objects into the participants field of view, bone conduction headphones sit on the temple of the participant, rather than in the ear canal, and so they do not diminish the ability to hear sounds originating from real (not virtual) objects or processes in their environment.

The content for this headset and headphones is visually and auditorily assembled in three dimensions by the Unity engine in conjunction with real-time head and hand tracking data! What a sentence, and what a feat in itself -- the credit for which lays soley with those genius minds that have enabled this open-source North Star project in the first place!

"So what are you looking (listening) for?"

I am interested in creating expressive musical instruments that are situated in AR; that is to say, they are spatially and contextually relevant to their real world environment, not only the virtual environment they are necessarily spawned into.

"Ok, but how will you make musical instruments in a 3D game engine?"

At this point, I would prefer to draw from an audio engine or audio-focused programming language that I already have some experience in, not only because it would be more familiar, but also because there are a few technical difficulties in trying to realise everything in Unity (more on that later). Sticking to one engine/language for prototyping audio interactions from the outset would be preferable in order to maintain progress and proficiency

"How will you choose from Supercollider, Max MSP, PureData, Wwise, and FMOD amongst others?"

In order to plan for the long-term relevance of this project in creating interactable, tangible, and expressive AR musical instruments, the features that this audio engine or audio-focused programming language would need are:

1. Uses In-Built Unity Audio Spatialisation

Unity is a great 3D engine, with native (in-built) spatialisation of creatable elements called "GameObjects", that can have:

(1) visual attributes such as three-dimensional meshes, material colours, and textural properties

(2) physical attributes such as edges, position, mass, velocity

(3) auditory attributes such as a sound source with pitch and volume dependent on the physical attributes of position and velocity (things further away from the AudioListener component, which is assigned to the position of the headset, are quieter for example)

For these reasons, keeping audio "inside" Unity, and using its native audio spatialisation based on physical transform (x,y,z, velocity etc) values of the GameObjects is a feature that the project would benefit massively from in terms of labour. If instead I chose to have a separate audio engine/server running in the background, it would have to have its own "knowledge" of the physical attributes of *all* of the GameObjects in Unity, and then spatialise everything itself. This (whilst possible) is probably outside of the scope of this project as long as an alternative is available that can exist "inside" Unity.

2. Cheap Instantiable Audio

The chosen audio engine / language needs to have the functionality of being able to create simple templates of audio algorithms that are then called into existence or "instantiated" tens to hundreds of times as the auditory output of certain GameObjects in Unity.

3. Extended Audio Techniques Available

It's not enough for the chosen audio engine/language to only have access to sample-based audio techniques (e.g. pressing a button triggers a pre-recorded sound file). It is definitely a feature I will need, as it is in cases more computationally "cheaper" to do so versus some synthesis techniques. However, due to the demands of real-time interaction in this project, and the aims of fine-grained expressive adaptation of musical textures, real-time synthesis will be one of the more often used techniques. More broadly and in the long-run, this project would benefit from being able to use as many audio techniques rather than having a cramped palette of 2 or 3 -- drawing from this early choice the ability to create a wide variety of AR musical instruments - each of them having their own nuanced interaction methods, creative expressivities, and modes sensory perception modulation.

4. Real-Time Parameter Control

Building on the last two features, the project would call for the ability to change in real-time, parameters of the audio algorithms being used. This would be the main source interactibility with an instrument, as having no parameters to control would likely mean that the instrument would not be instrumental in doing anything. Additionally, it would reduce the extent of co-adaptation of musical textures between participant and their instrument if there were not any parameters of the sound that were effectable in real-time. Therefore, this audio engine/language must have the ability to expose its own parameters to Unity via C# scripting (which is the native language of Unity projects) so that attributes and values inherent to the associated GameObjects can be mapped to have effects on the audio algorithms. This would make interactions such as touching an object (which is an event that happens in Unity) be able to have effects such as increasing the pitch of the sound coming out of the object, randomising the volume, or changing the scale (which would be values inside the audio engine/language).

5. Allows Rapid Prototyping

In order to iterate quickly and efficiently on the design of instruments, whatever engine or language I am using must support quick changes to the structure and logic of the instrument and its audiovisual properties.

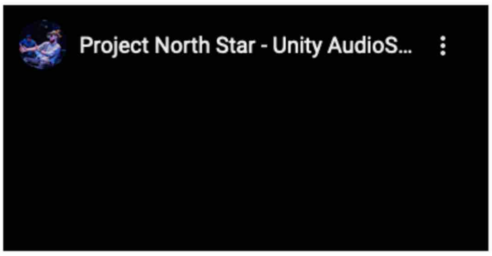
6. Open-Source, Free, and Cross-Platform

It would be preferable that this audio engine/language is open-source, free and cross-platform in order to be as inclusive as possible to a wide range of computational artists, designers, and developers wanting to implement and make their own AR musical instruments.

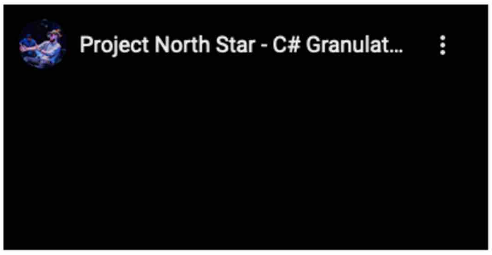
What to use then?

The following are only some of the available options, but are those that tick the most boxes feature-wise.

Unity's AudioSource Component

Rating	Notes
★★★★★ Uses Unity Spatialisation ★★★★★ Cheap Instantiable Audio ★★☆☆☆ Extended Audio Techniques Available ★★★☆☆ Real-Time Parameter Control ★★★☆☆ Allows Rapid Prototyping ★★★★★ Open-Source, Free, and Cross-Platform	No real-time synthesis means that instruments would be fairly simple sample triggerers with not much parameterisation available. 

C# Granulator Synth via Granulator

Rating	Notes
★★★★★ Uses Unity Spatialisation ★★★★★ Cheap Instantiable Audio ★★★☆☆ Extended Audio Techniques Available ★★★★☆ Real-Time Parameter Control ★★★☆☆ Allows Rapid Prototyping ★★★★★ Open-Source, Free, and Cross-Platform	Granular synthesis only, would be a fairly limited set of options for building parameterised instruments. 

Supercollider

Rating	Notes
☆☆☆☆☆ Uses Unity Spatialisation ★★★★★ Cheap Instantiable Audio ★★★★☆ Extended Audio Techniques Available ★★★★★ Real-Time Parameter Control ★★★★★ Allows Rapid Prototyping	No integration with Unity means two engines running (scsynth+Unity), and hence there would be a lot of work associated with attaining the same level of 3D audio believability that Unity provides natively. I would have to send all GameObject object, head, hand transforms to Supercollider and re-create the 3D

★★★★★ Open-Source, Free, and Cross-Platform

engine environment before even getting to synthesis.

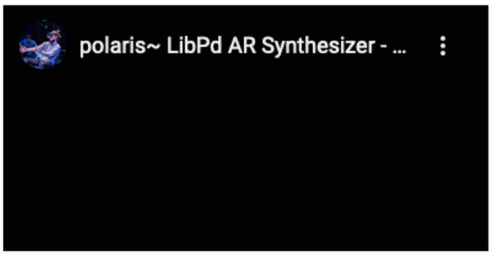
MaxMSP

Rating	Notes
☆☆☆☆☆ Uses Unity Spatialisation ★★★★☆ Cheap Instantiable Audio ★★★★★ Extended Audio Techniques Available ★★★★★ Real-Time Parameter Control ★★★★★ Allows Rapid Prototyping ★☆☆☆☆ Open-Source, Free, and Cross-Platform	Same issue as Supercollider, but is also not free nor open-source.

Pure Data via Heavy Compiler and Wwise

Rating	Notes
☆☆☆☆☆ Uses Unity Spatialisation ★★★☆☆ Cheap Instantiable Audio ★★★★★ Extended Audio Techniques Available ★★★★★ Real-Time Parameter Control ★☆☆☆☆ Allows Rapid Prototyping ★☆☆☆☆ Open-Source, Free, and Cross-Platform	Not being comfortable with Wwise means this is a poor option. It would also require using a separate 3D audio engine such as Resonance or Microsoft 3D Audio. It would be slow to prototype due to the time compiling patches into C for Wwise.

Pure Data via LibPdIntegration

Rating	Notes
★★★★★ Uses Unity Spatialisation ★★★★★ Cheap Instantiable Audio ★★★★★ Extended Audio Techniques Available ★★★★★ Real-Time Parameter Control ★★★★★ Allows Rapid Prototyping ★★★★★ Open-Source, Free, and Cross-Platform	This is the way to go! 

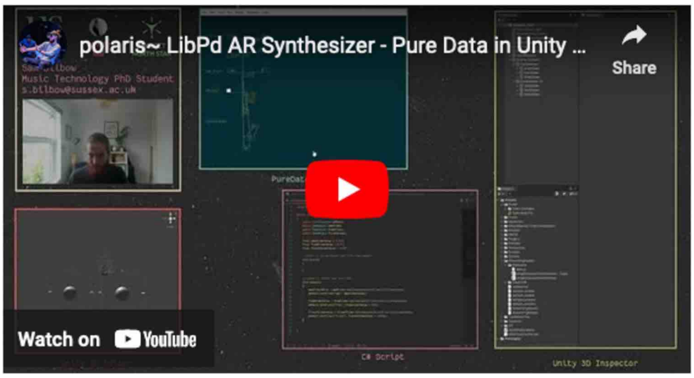
B.3.7 Software: Musical AR Instruments in PureData

Software: Musical AR Instruments in PureData (August 2021 – Ongoing)

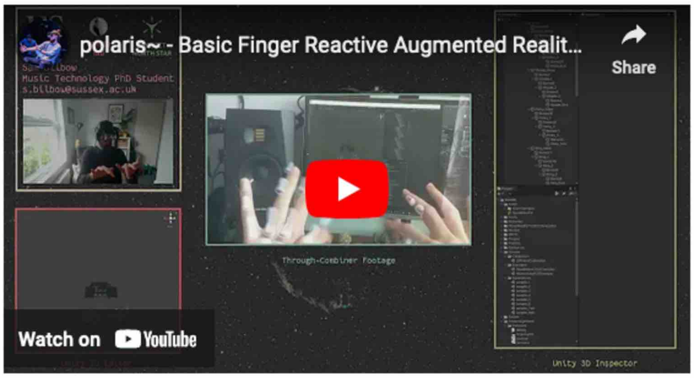
The NEW Current state of the ARt

In the last section, I went through the available choices for developing the audio section of my AR instruments. Out of these choices, the system that makes the most sense is developing PureData patches for the audio end of the instrument, and then implementinng Niall Moody's LibPdIntegration project, which allows PureData patches to be run in Unity.

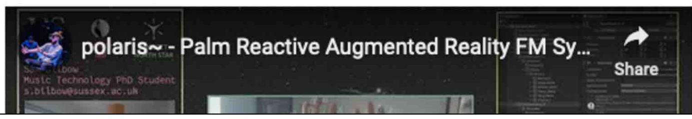
Parameterised GameObject AR Synthesizers

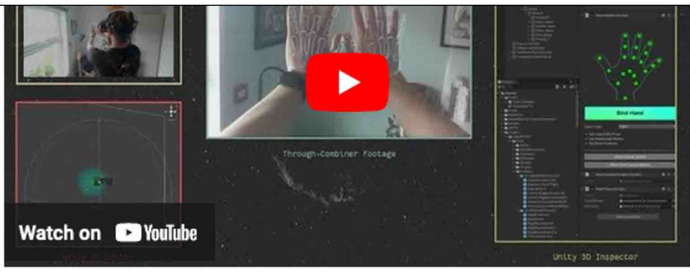


Finger Reactive (10x synth gens) AR Synthesiser

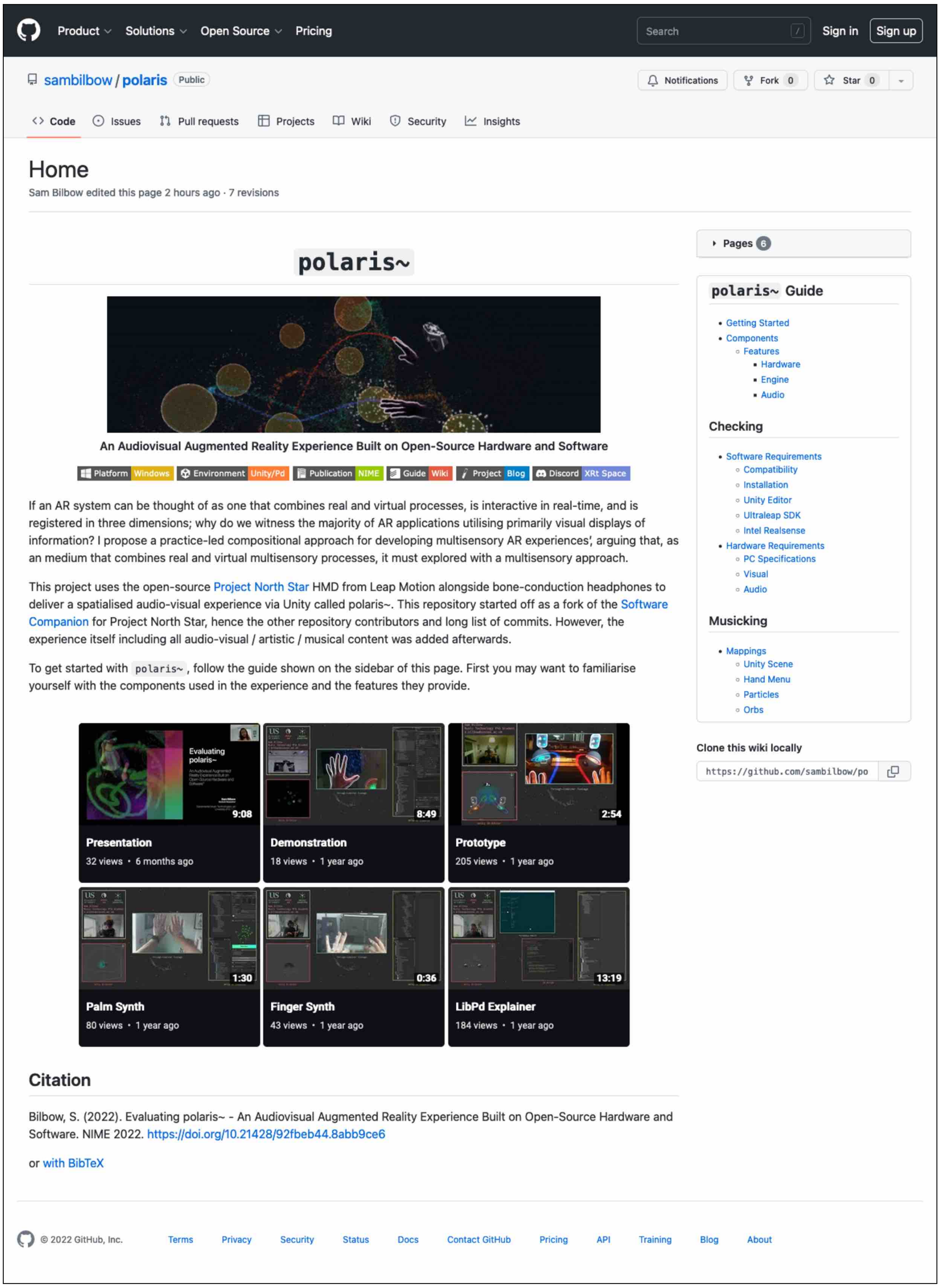


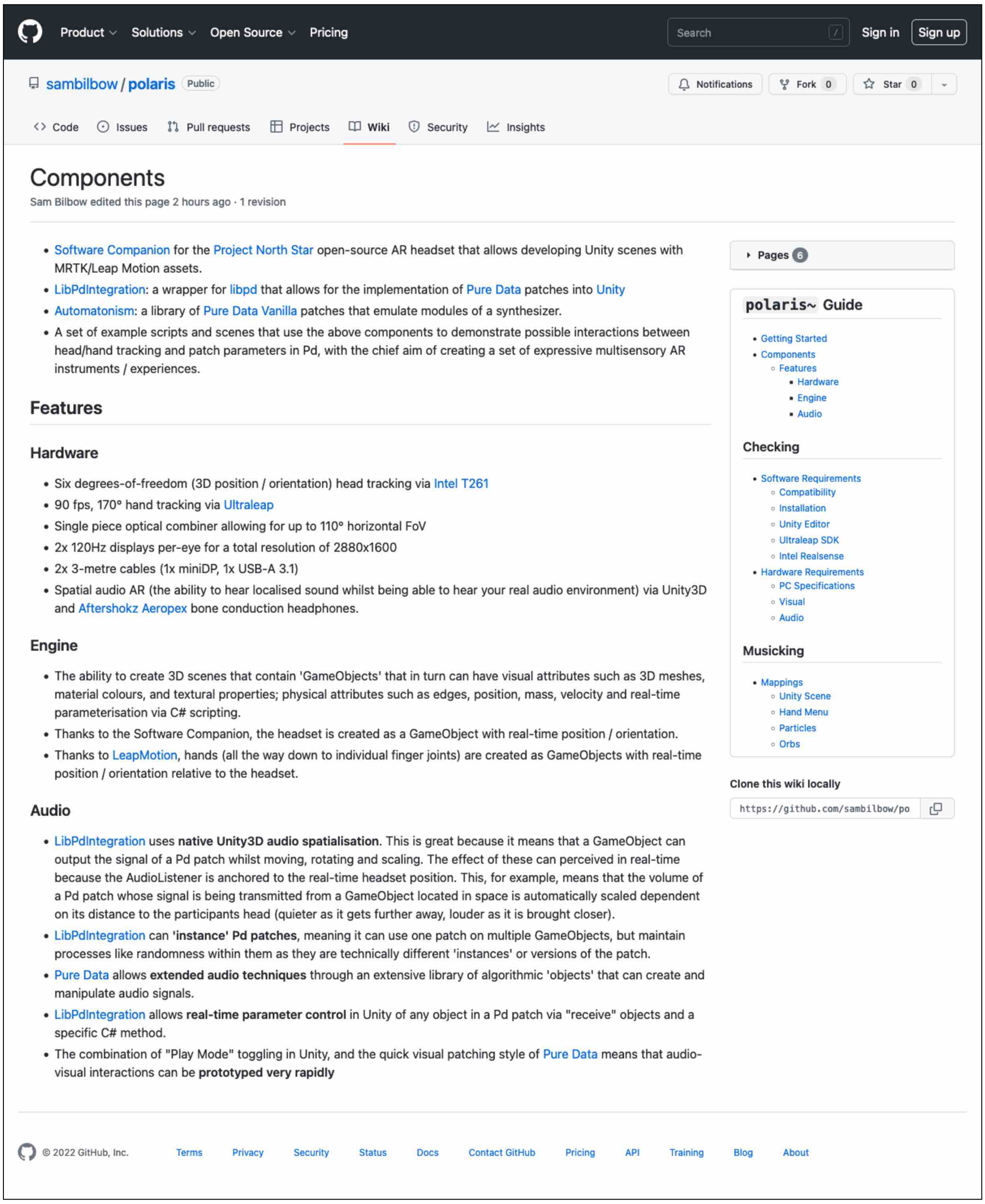
Palm Reactive (2x synth gens) AR Synthesiser




Through-Combiner Footage
Unity 3D Inspector
Watch on YouTube

B.4 polaris~ Project Guide





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Components

Sam Bilbow edited this page 2 hours ago · 1 revision

- Software Companion for the Project North Star open-source AR headset that allows developing Unity scenes with MRTK/Leap Motion assets.
- LibPdIntegration: a wrapper for libpd that allows for the implementation of Pure Data patches into Unity
- Automatonism: a library of Pure Data Vanilla patches that emulate modules of a synthesizer.
- A set of example scripts and scenes that use the above components to demonstrate possible interactions between head/hand tracking and patch parameters in Pd, with the chief aim of creating a set of expressive multisensory AR instruments / experiences.

Features

Hardware

- Six degrees-of-freedom (3D position / orientation) head tracking via Intel T261
- 90 fps, 170° hand tracking via Ultraleap
- Single piece optical combiner allowing for up to 110° horizontal FoV
- 2x 120Hz displays per-eye for a total resolution of 2880x1600
- 2x 3-metre cables (1x miniDP, 1x USB-A 3.1)
- Spatial audio AR (the ability to hear localised sound whilst being able to hear your real audio environment) via Unity3D and Aftershokz Aeropex bone conduction headphones.

Engine

- The ability to create 3D scenes that contain 'GameObjects' that in turn can have visual attributes such as 3D meshes, material colours, and textural properties; physical attributes such as edges, position, mass, velocity and real-time parameterisation via C# scripting.
- Thanks to the Software Companion, the headset is created as a GameObject with real-time position / orientation.
- Thanks to LeapMotion, hands (all the way down to individual finger joints) are created as GameObjects with real-time position / orientation relative to the headset.

Audio

- LibPdIntegration uses **native Unity3D audio spatialisation**. This is great because it means that a GameObject can output the signal of a Pd patch whilst moving, rotating and scaling. The effect of these can perceived in real-time because the AudioListener is anchored to the real-time headset position. This, for example, means that the volume of a Pd patch whose signal is being transmitted from a GameObject located in space is automatically scaled dependent on its distance to the participants head (quieter as it gets further away, louder as it is brought closer).
- LibPdIntegration can **'instance' Pd patches**, meaning it can use one patch on multiple GameObjects, but maintain processes like randomness within them as they are technically different 'instances' or versions of the patch.
- Pure Data allows **extended audio techniques** through an extensive library of algorithmic 'objects' that can create and manipulate audio signals.
- LibPdIntegration allows **real-time parameter control** in Unity of any object in a Pd patch via "receive" objects and a specific C# method.
- The combination of "Play Mode" toggling in Unity, and the quick visual patching style of Pure Data means that audio-visual interactions can be **prototyped very rapidly**

Pages 6

polaris~ Guide

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  - Installation
  - Unity Editor
  - Ultraleap SDK
  - Intel Realsense
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- Mappings
  - Unity Scene
  - Hand Menu
  - Particles
  - Orbs

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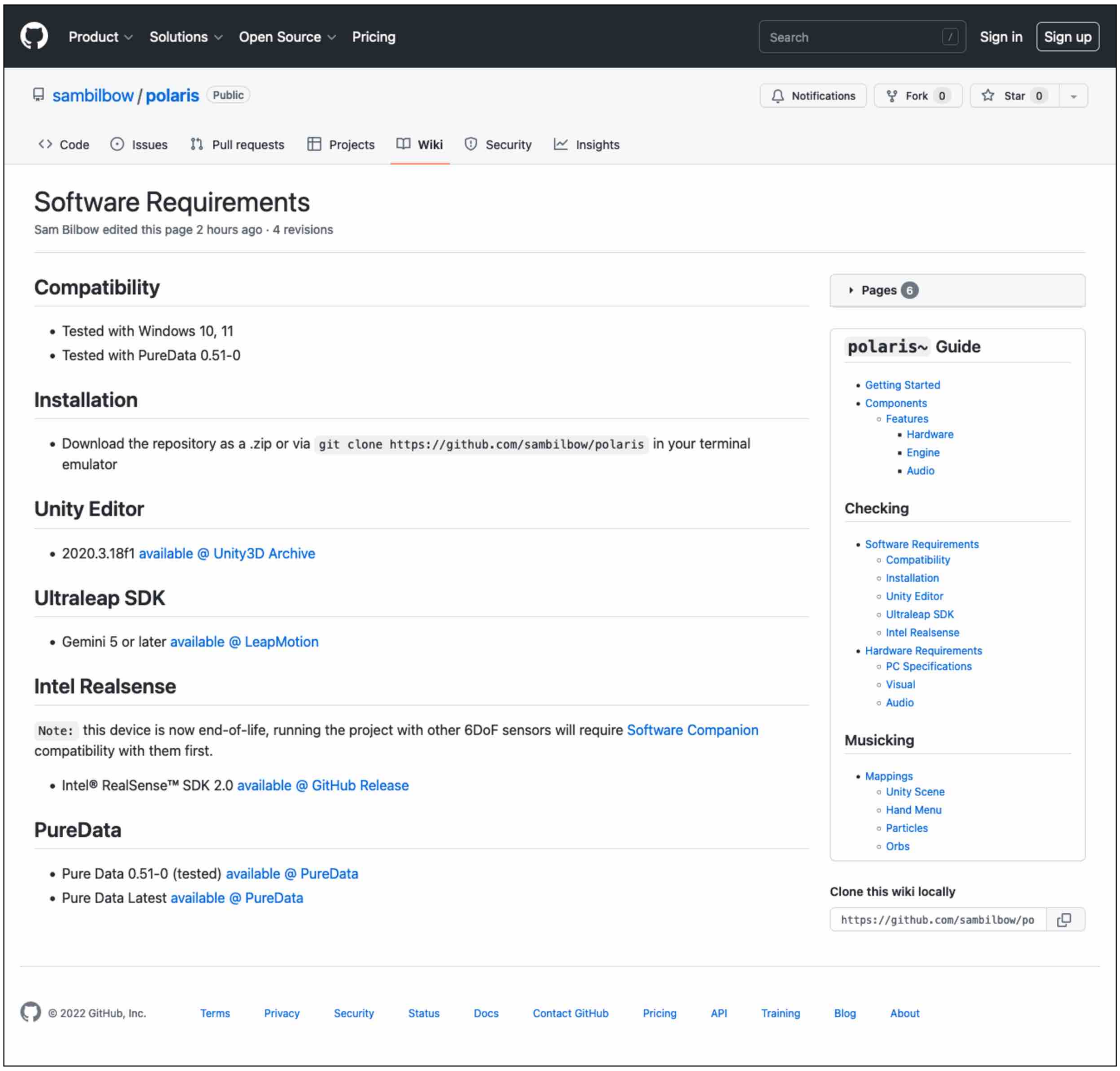
https://github.com/sambilbow/po


Product Solutions Open Source Pricing
Search
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Sign up
sambilbow / polaris Public
Notifications
Fork 0
Star 0
Code Issues Pull requests Projects Wiki Security Insights
Software Requirements
Sam Bilbow edited this page 2 hours ago · 4 revisions
Compatibility
Tested with Windows 10, 11
Tested with PureData 0.51-0
Installation
Download the repository as a .zip or via git clone https://github.com/sambilbow/polaris in your terminal emulator
Unity Editor
2020.3.18f1 available @ Unity3D Archive
Ultraleap SDK
Gemini 5 or later available @ LeapMotion
Intel Realsense
Note: this device is now end-of-life, running the project with other 6DoF sensors will require Software Companion compatibility with them first.
Intel® RealSense™ SDK 2.0 available @ GitHub Release
PureData
Pure Data 0.51-0 (tested) available @ PureData
Pure Data Latest available @ PureData
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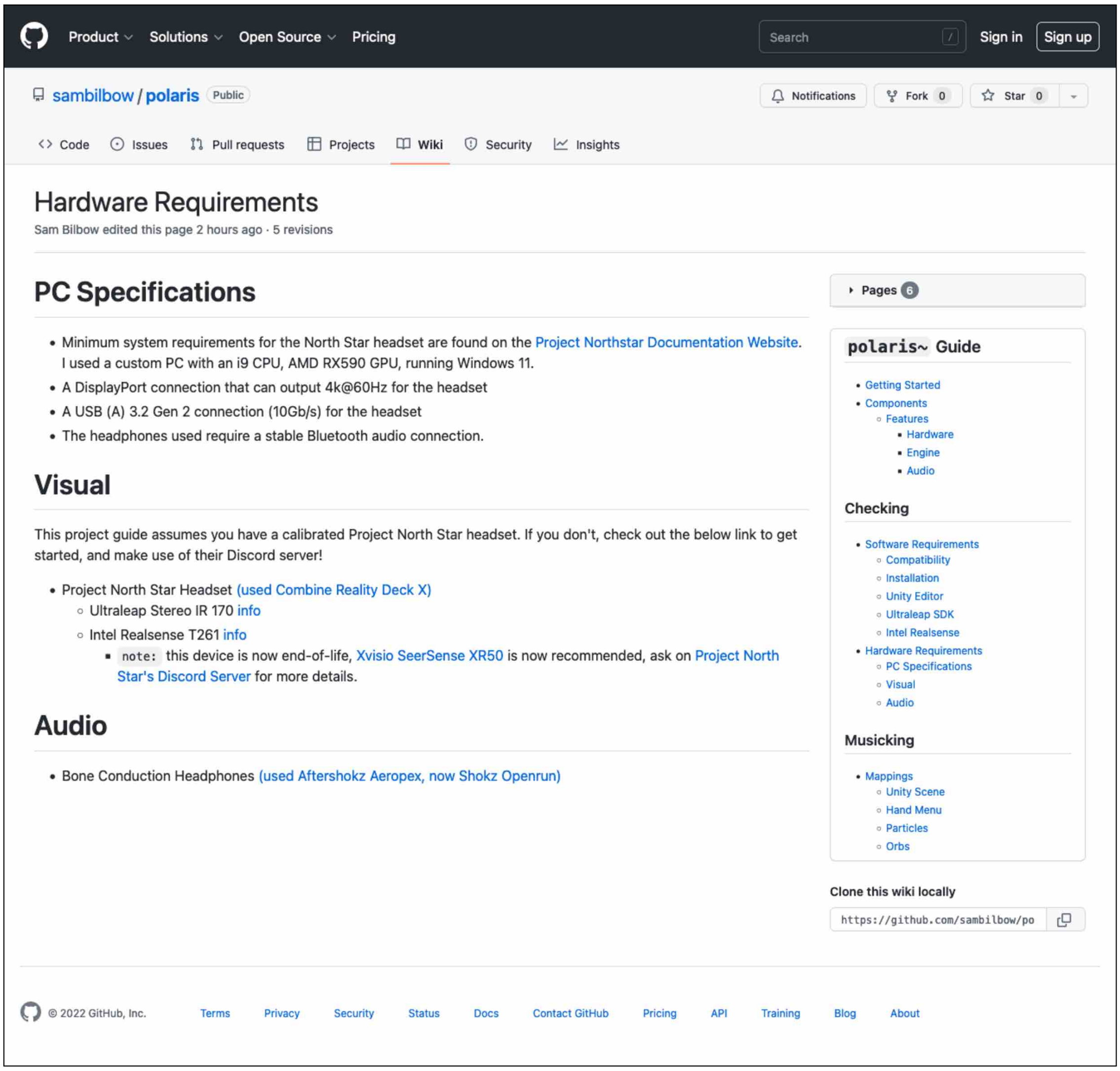

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Hardware Requirements

Sam Bilbow edited this page 2 hours ago · 5 revisions

PC Specifications

- Minimum system requirements for the North Star headset are found on the Project Northstar Documentation Website. I used a custom PC with an i9 CPU, AMD RX590 GPU, running Windows 11.
- A DisplayPort connection that can output 4k@60Hz for the headset
- A USB (A) 3.2 Gen 2 connection (10Gb/s) for the headset
- The headphones used require a stable Bluetooth audio connection.

Visual

This project guide assumes you have a calibrated Project North Star headset. If you don't, check out the below link to get started, and make use of their Discord server!

- Project North Star Headset (used Combine Reality Deck X)
  - Ultraleap Stereo IR 170 info
  - Intel Realsense T261 info
    - `note:` this device is now end-of-life, Xvisio SeerSense XR50 is now recommended, ask on Project North Star's Discord Server for more details.

Audio

- Bone Conduction Headphones (used Aftershokz Aeropex, now Shokz Openrun)

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polaris~ Guide

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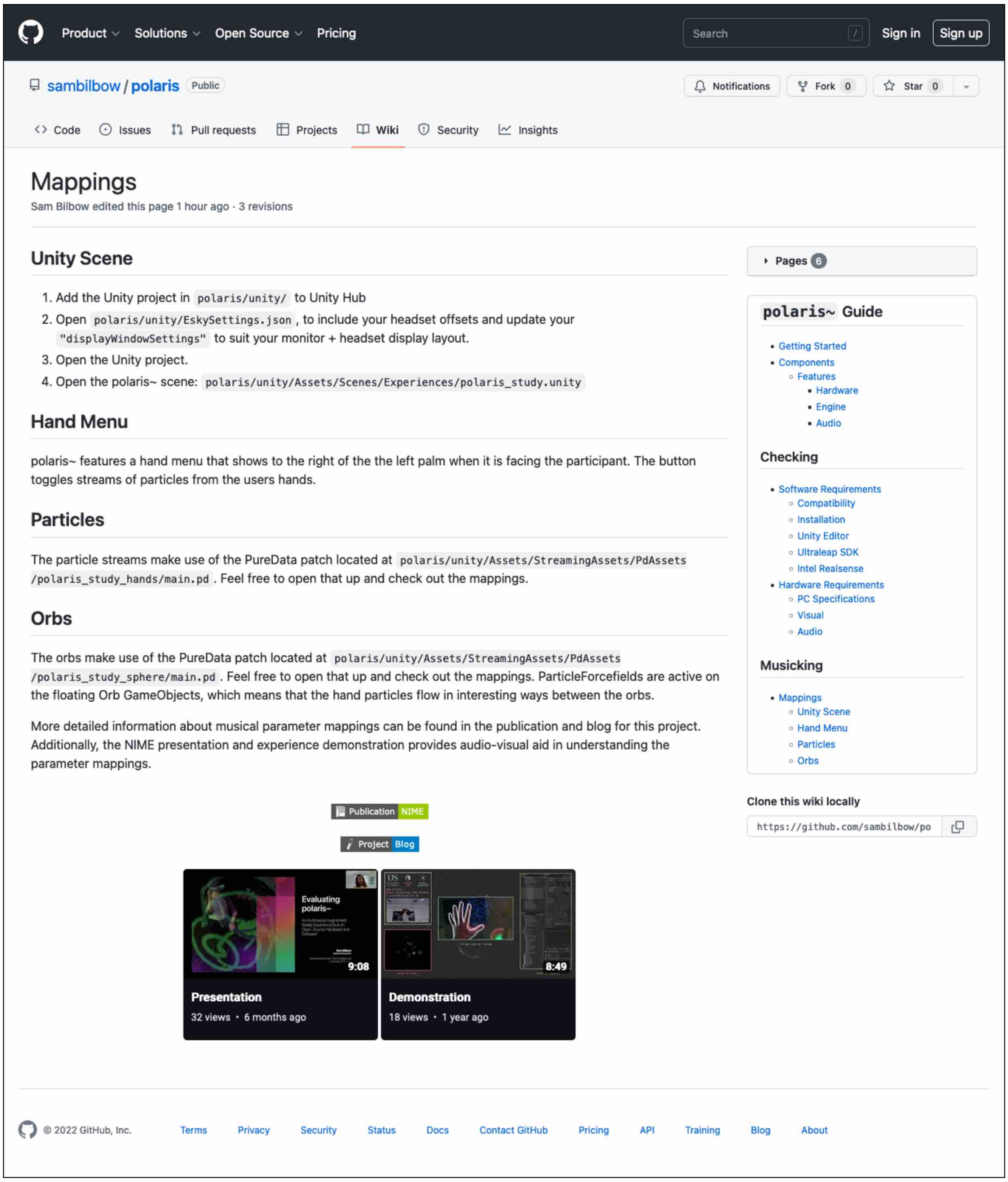
`https://github.com/sambilbow/po`



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Mappings

Sam Bilbow edited this page 1 hour ago · 3 revisions

Unity Scene

1. Add the Unity project in `polaris/unity/` to Unity Hub
2. Open `polaris/unity/EskySettings.json`, to include your headset offsets and update your `"displayWindowSettings"` to suit your monitor + headset display layout.
3. Open the Unity project.
4. Open the polaris~ scene: `polaris/unity/Assets/Scenes/Experiences/polaris_study.unity`

Hand Menu

polaris~ features a hand menu that shows to the right of the the left palm when it is facing the participant. The button toggles streams of particles from the users hands.

Particles

The particle streams make use of the PureData patch located at `polaris/unity/Assets/StreamingAssets/PdAssets/polaris_study_hands/main.pd`. Feel free to open that up and check out the mappings.

Orbs

The orbs make use of the PureData patch located at `polaris/unity/Assets/StreamingAssets/PdAssets/polaris_study_sphere/main.pd`. Feel free to open that up and check out the mappings. ParticleForcefields are active on the floating Orb GameObjects, which means that the hand particles flow in interesting ways between the orbs.

More detailed information about musical parameter mappings can be found in the publication and blog for this project. Additionally, the NIME presentation and experience demonstration provides audio-visual aid in understanding the parameter mappings.

Publication NIME

Project Blog

Evaluating polaris~ 9:08

Presentation

32 views • 6 months ago

8:49

Demonstration

18 views • 1 year ago

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polaris~ Guide

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- Components
  - Features
    - Hardware
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B.5 polaris~ Study Documents

B.5.1 Ethics Approval

UNIVERSITY OF SUSSEX

Social Sciences & Arts C-REC
c-recss@admin.susx.ac.uk

Certificate of Approval	
Reference Number	ER/SMB44/3
Title Of Project	Augmented Reality Experiences with Project North Star: Pilot Iterative Design
Principal Investigator (PI):	Sam Bilbow
Student	Sam Bilbow
Collaborators	
Duration Of Approval	3 months
Expected Start Date	26-Jul-2021
Date Of Approval	26-Jul-2021
Approval Expiry Date	31-Oct-2021
Approved By	Vacancy
Name of Authorised Signatory	Ruth Stirton
Date	26-Jul-2021

*NB. If the actual project start date is delayed beyond 12 months of the expected start date, this Certificate of Approval will lapse and the project will need to be reviewed again to take account of changed circumstances such as legislation, sponsor requirements and University procedures.

Please note and follow the requirements for approved submissions:

Amendments to protocol

* Any changes or amendments to approved protocols must be submitted to the C-REC for authorisation prior to implementation.

Feedback regarding the status and conduct of approved projects

* Any incidents with ethical implications that occur during the implementation of the project must be reported immediately to the Chair of the C-REC.

Feedback regarding any adverse(1) and unexpected events(2)

* Any adverse (undesirable and unintended) and unexpected events that occur during the implementation of the project must be reported to the Chair of the Social Sciences and Arts C-REC. In the event of a serious adverse event, research must be stopped immediately and the Chair alerted within 24 hours of the occurrence.

Monitoring of Approved studies

The University may undertake periodic monitoring of approved studies. Researchers will be requested to report on the outcomes of research activity in relation to approvals that were granted (full applications and amendments).

Research Standards

Failure to conduct University research in alignment with the Code of Practice for Research may be investigated under the Procedure for the Investigation of Allegations of Misconduct in Research or other appropriate internal mechanisms (3). Any queries can be addressed to the Research Governance Office: rgoffice@sussex.ac.uk

(1) An "adverse event" is one that occurs during the course of a research protocol that either causes physical or psychological harm, or increases the risk of physical or psychological harm, or results in a loss of privacy and/or confidentiality to research participant or others.

(2) An "unexpected event" is an occurrence or situation during the course of a research project that was a) harmful to a participant taking part in the research, or b) increased the probability of harm to participants taking part in the research.

(3) http://www.sussex.ac.uk/staff/research/rqi/policy/research-policy

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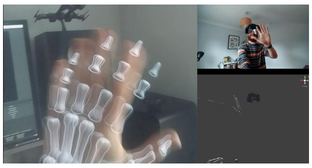
B.5.2 Recruitment

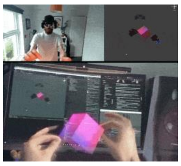
UNIVERSITY OF SUSSEX

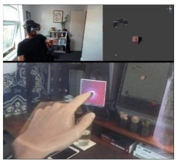
Augmented Reality Experiences with Project North Star: Pilot Iterative Design
RECRUITMENT EMAIL

Subject: [Looking for participants] Take part in an immersive audio-visual Augmented Reality study!

Introduction
Hello! I am a music technology PhD student in my 2nd year in the School of Media, Arts and Humanities. I am currently looking for a **diverse** and **inclusive** range of 8 participants who would be available during [August and September] to **individually** user-test prototyped Augmented Reality experiences that deliver creative and expressive audio-visual content.







Details
The study would take place on **campus**, would take **45 minutes** to **1 hour**, and would involve a brief questionnaire, a tutorial, a "free-roam" in the 3D AR audio-visual scene, followed by an informal interview of your experience. You would be compensated **£15** for your time, in the form of a [x]. Taking part in this study would also be a great opportunity for anyone who has not yet experienced AR/VR technologies which are often prohibitively expensive.

Context
Typically, these technologies focus on visual experience of layering virtual objects. My PhD aims to resituate AR as a sensory experience that not only aims to layer objects onto our real world, but mix, diminish, and extend our reality through multisensory scenes.

The headset being used, Project North Star, is an open-source, community driven project that aims to make cutting-edge hand/head/body tracking in AR readily available at a cost that is not prohibitive for DIY hackers and makers. For audio, separate wireless bone-conduction headphones are utilised in order to blend real-virtual auditory perception.

Augmented Reality Experiences with Project North Star: Pilot Iterative Design

Page 1 of 2

Recruitment Email
Version 1
17/07/2021

Thank you taking the time to read this email! I'm looking forward to hearing from you. If you are interested in more, binaural videos of what experience is like through-the-headset are on my YouTube channel.
Sam

____

Sam Bilbow
PhD Student in Computational Art & Augmented Reality
Department of Music
School of Media, Arts and Humanities
University of Sussex

B.5.3 Information Sheet

Augmented Reality Experiences with Project North Star: Pilot Iterative Design
PARTICIPANT INFORMATION SHEET

Invitation
You are being invited to take part in a research study. Before you decide whether or not to take part, it is important for you to understand why research is being done and what it will involve. Please take the time to read the following information carefully.

What is the purpose of the study?
This study aims to gather insight into behaviours and intuitions of participants who are wearing and interacting with an augmented reality headset and headphones. The experience will focus on delivering audio-visual 3D virtual objects that appear to be localised in the real world through the lens and headphones of these devices. You will be encouraged to move and manipulate these objects in any way you see fit thereby exercising your creativity and ability to gesturally express yourself.

Do I have to take part?
It is up to you to decide whether to take part. If you **do** decide to take part, you will be given this information sheet to keep and be asked to **sign a consent form**. You are still **free to withdraw** at any time and **without giving a reason**.

For students: taking part or not taking part in this study will have **no** impact on your marks, assessments, or future studies.

What will happen to me if I take part?
Agreeing to take part in this study will mean that upon reading the information sheet and signing the consent form, you will

- Complete a short questionnaire based on your familiarity with similar technologies, musical instrument, and artistic abilities.
- Be inducted via a brief and informal tutorial section that introduces you to the devices (a headset and specialist headphones) and their capabilities, including ways in which you may want to interact in the scene with them.
- Independently explore the audio-visual scene via augmented reality devices.
- Partake in a short interview about the experience of the devices, and the blended real/virtual experience that you interacted with.

What are the possible disadvantages of taking part?
This study will take approximately 45 minutes to 1 hour.

What are the possible benefits of taking part?
Taking part in this study will grant you the opportunity to interact with cutting edge hand and head tracking technologies. Typically, in AR studies, this technology is only available as part of extremely expensive and delicate equipment. This is however, not true in this case due to the open-source and DIY nature of this headset.

Additionally, you will be directly benefitting the open-source community that contributes to the design of the AR headset and its software framework. Your interaction in this study will grant further understanding to intuitive interactions within expressive audio-visual experiences of AR devices and content.

Will my information in this study be kept confidential?
Your information will be kept strictly confidential. Contributions to the study via your questionnaire and interview answers and your activity with the headset and the content that it displays audio-visually will be anonymised so that there is no identifiable factors within its use in storage and publication of resultant research material.

What will happen to the results of the research study?
The anonymised results of this research study will be used in my music technology PhD thesis and may also be published. To obtain a copy of the published work please contact me.

Who is organising and funding the research?
I am conducting this research as a PGR student of the University of Sussex (School of Media, Arts and Humanities). My research is funded by the Leverhulme Trust via their Doctoral Scholarship Programme at the University of Sussex.

Who has approved this study?
This study has been approved by the Social Sciences & Arts Cross-Schools Research Ethics Committee. The reference number is ER/SMB44/3

Contact for Further Information
Researcher Name: Sam Bilbow
Researcher Email: s.bilbow@sussex.ac.uk

Supervisor Names: Dr. Chris Kiefer
Dr. Cécile Chevalier

Supervisor Emails: c.kiefer@sussex.ac.uk
c.chevalier@sussex.ac.uk

Insurance
The University of Sussex has insurance in place to cover its legal liabilities in respect of this study.

Thank you for taking the time to read this information sheet.

Augmented Reality Experiences with Project North Star: Pilot Iterative Design

Page 2 of 2

Information Sheet
Version 3
26/09/2021

B.5.4 Consent Form

UNIVERSITY OF SUSSEX

CONSENT FORM FOR PROJECT PARTICIPANTS DOING INDIVIDUAL INTERVIEWS

Title of Project: Augmented Reality Experiences with Project North Star: Pilot Iterative Design
Name of Researcher and School: Sam Bilbow, Media, Arts and Humanities
C-REC Ref no: ER/SMB44/3

	Please tick box (YES / NO)	
• *I agree to allowing the study to be video recorded for transcription purposes*	☐	☐
• *I agree to fill out a questionnaire provided by the researcher*	☐	☐
• *I agree to equip the headset and headphones as part of the study*	☐	☐
• *I consent to being interviewed by the researcher about my experience*	☐	☐
• *I agree for the use of my email for further correspondence relating to the study*	☐	☐
• *I agree to making myself available for a further interview should it be required*	☐	☐
• *I understand that I will be given a transcript of data concerning me for my approval before being included in the write up of the research*	☐	☐
• *I understand that I will be given a transcript of any data that I have provided for my approval before being included in the write up of the research*	☐	☐
• *I consent to the use of anonymised quotes in publications from the research*	☐	☐
• *I consent to the use of anonymised photos in publications from the research*	☐	☐
• *I understand that in exceptional circumstances e.g. where the health, welfare and safety of myself or others is compromised by information I might disclose, the researcher will be legally required to pass this information onto an appropriate individual or agency.*	☐	☐

Augmented Reality Experiences with Project North Star: Pilot Iterative Design

Page 1 of 2

Consent Form
Version 2
08/10/2021

• *I understand that any information I provide is confidential, and that no information that I disclose will lead to the identification of any individual in the reports on the project, either by the researcher or by any other party*	☐	☐
• *I have read the information sheet, had the opportunity to ask questions and I understand the principles, procedures and possible risks involved.*	☐	☐
• *I understand that my personal data will be used for the purposes of this research study. I understand that such information will be treated as strictly confidential and handled in accordance with data protection legislation.*	☐	☐
• *I understand that my participation is voluntary, that I can choose not to participate in part or all of the project, and that I can withdraw at any stage of the project without being penalised or disadvantaged in any way nor do I have to give reasons for this.*	☐	☐
• *I consent to my data being deposited in the UK Data Archive for re-use in future research and analysis. I understand that it will be fully anonymised before deposit.*	☐	☐
• *I agree to take part in the above University of Sussex research project*	☐	☐

Name:

Signature:

Date:

B.5.5 Questionnaire

UNIVERSITY OF SUSSEX

Augmented Reality Experiences with Project North Star: Pilot Iterative Design
QUESTIONNAIRE FOR PARTICIPANTS

Age: ___________ ☐ Prefer not to say

Gender: ___________ ☐ Prefer not to say

Ethnicity: ___________ ☐ Prefer not to say

Occupation: ___________ ☐ Prefer not to say

1. In the last year, how frequently have you experienced content via **augmented** reality headsets (e.g. Hololens, Magic Leap etc.)?

None 1 – 5 times 5 – 10 times 10 – 15 times 15+ times

2. In the last year, how frequently have you experienced content via **virtual** reality headsets (e.g. Vive, Oculus, Index, PSVR etc.)?

None 1 – 5 times 5 – 10 times 10 – 15 times 15+ times

3. What experience (if any) do you have with **gesturally dependent technologies** such as hand, head or body tracking via controllers or cameras (e.g. Kinect, PS Move, Wii etc.)?

No experience Limited experience Working experience Proficient Expert

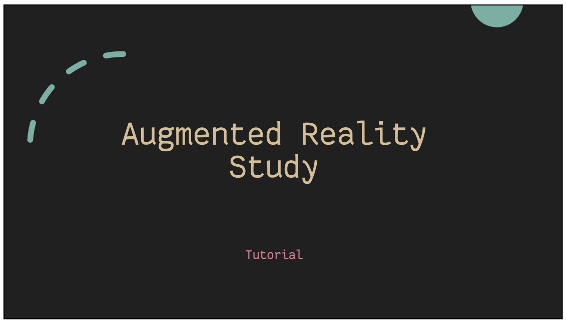
4. Do you practice any **musical instrument** (traditional or novel)? If yes, which ones, for how long have you done this, and how many years of formal training do you have?

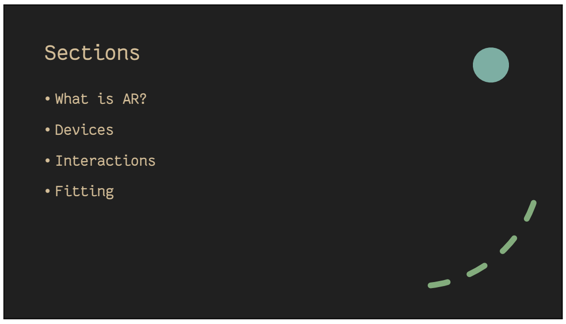
Musical Instrument	Years of Experience	Years of Training

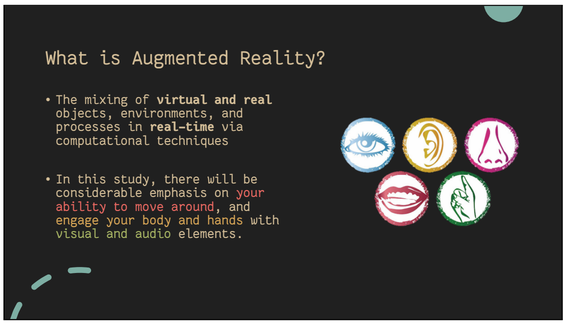
5. Do you practice any **visual art or craft** (traditional or novel) If yes, which ones, for how long have you done this, and how many years of formal training do you have?

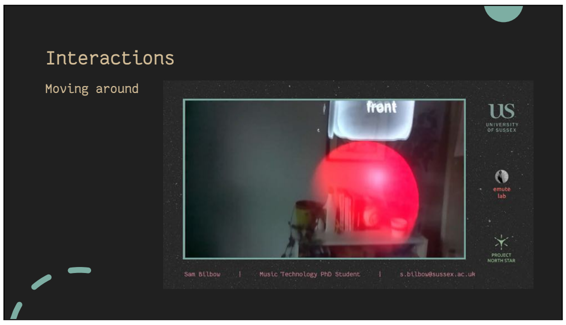
Visual Art / Craft	Years of Experience	Years of Training

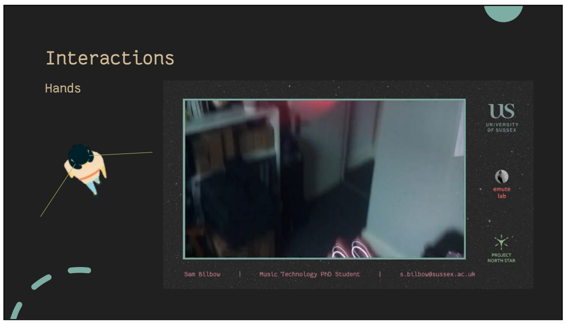
B.5.6 Tutorial

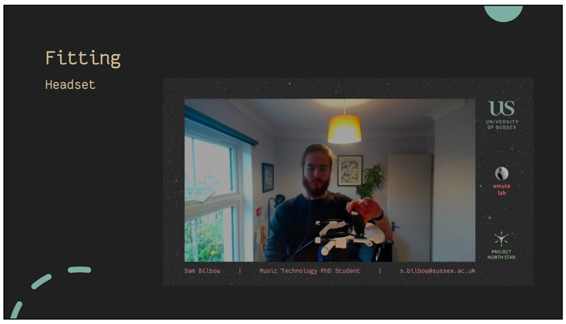


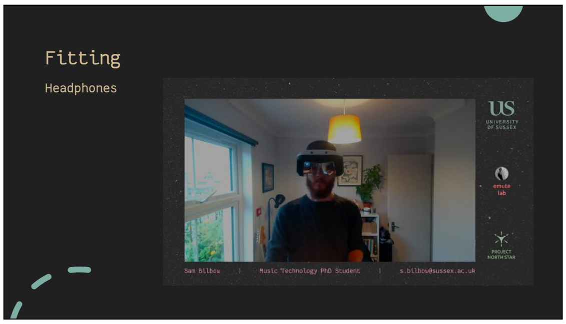












B.5.7 Interview Topic Guide

Augmented Reality Experiences with Project North Star: Pilot Iterative Design
TOPIC GUIDE FOR INTERVIEW

This topic guide takes some of it pointers from Katy Tcha-Tokey and collaborators' paper: "Proposition and Validation of a Questionnaire to Measure the User Experience in Immersive Virtual Environments" (Tcha-Tokey et al., 2016), which although tailored for Virtual Reality experiences, can be drawn from and modified to survey experience of Augmented Reality too. The appendix of the paper includes the full translated 68 questions.

Starting with the introductory questions of:

1. What were some positive aspects about your experience in the environment?
2. What were some negative aspects about your experience in the environment?
3. Do you have any other suggestions to improve this augmented reality environment or the experience in general?

I will follow the experience remarks given by the participant and guide the conversation and questions towards the following general areas:

- Presence (e.g. 15. *Can you correctly localise sounds being produced by the augmented environment?*)
- Immersion (e.g. 16. *Do you feel stimulated by the augmented environment?*)
- Engagement (e.g. 6. *How compelling is the sense of moving around inside the augmented environment?*)
- Flow (e.g. 23. *Do you feel like you can control your actions?*)
- Skill (e.g. 53. *How confident do you feel moving items in this augmented environment?*)
- Emotion (e.g. 37. *Are you enjoying being inside this augmented environment?*)
- Experience Consequence (e.g. 62. *Did you suffer from fatigue during your interaction?*)
- Judgement (e.g. 58. *Would you say that the environment is unruly or manageable?*)
- Technology Adoption (e.g. 72. *How difficult would it be for you to become skilful at this environment?*)

Bibliography

Tcha-Tokey, K., Christmann, O., Loup-Escande, E., & Richir, S. (2016). Proposition and Validation of a Questionnaire to Measure the User Experience in Immersive Virtual Environments. *International Journal of Virtual Reality*, *16*(1), 33–48. https://doi.org/10.20870/IJVR.2016.16.1.2880

Appendix

Modified questions from the Questionnaire for User Experience in Immersive Virtual Environements

Presence

- My interactions with the virtual environment seemed natural.
- The devices which controlled my movement in the virtual environment seemed natural.
- I could actively survey the virtual environment using vision.
- I could examine objects closely.
- I could examine objects from multiple viewpoints.
- I felt proficient in moving and interacting with the virtual environment at the end of the experience.
- I could concentrate on the content of the experience rather than on the headset itself.
- I correctly localized sounds produced by the virtual environment.

Engagement

- The visual aspects of the virtual environment involved me.
- The auditory aspects of the virtual environment involved me.
- The sense of moving around inside the virtual environment was compelling.
- I was involved in the virtual environment experience.

Immersion

- I felt stimulated by the virtual environment.
- I become so involved in the virtual environment that I was not aware of things happening around me.
- I felt physically fit in the virtual environment.
- I became so involved in the virtual environment that I lost all track of time.

Flow

- I felt I could perfectly control my actions.
- At each step, I knew what to do.
- I felt I controlled the situation.
- Time seemed to flow differently than usual.
- Time seemed to speed up.
- I was losing the sense of time.
- I was not worried about what other people would think of me.
- I felt I was experiencing an exciting moment.
- This experience was giving me a great sense of well-being
- When I mention the experience in the virtual environment, I feel emotions I would like to share.

Emotion

- I enjoyed being in this virtual environment.
- It was so exciting that I could stay in the virtual environment for hours.
- I enjoyed the experience so much that I feel energized.
- I felt nervous in the virtual environment.
- I felt like distracting myself in order to reduce my anxiety.
- I found my mind wandering while I was in the virtual environment.
- The interaction devices (headset and headphones) bored me to death.
- When my actions were going well, it gave me a rush.
- While using the interaction devices (headset and headphones), I felt like time was dragging.
- I enjoyed the challenge of learning the virtual reality interaction devices (headset and headphones)
- I enjoyed dealing with the interaction devices (headset and headphones).

Skill
- I felt confident interacting with objects in the virtual environment.
- I felt confident keeping my hands tracked (outline) around the virtual environment.
- I feel confident understanding the terms/words relating to the interaction devices (headset and headphones).
- I feel confident learning advanced skills within a specific augmented reality experience using these devices.
- I feel confident describing the functions the interaction devices (headset and headphones).

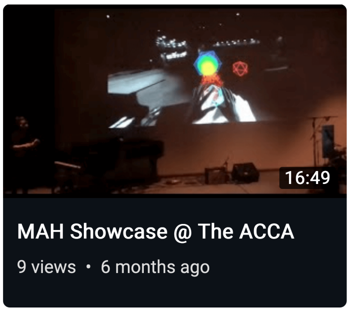
Judgement
- Did you find the virtual environment impractical/practical
- Did you find the virtual environment confusing/clear
- Did you find the virtual environment unruly/manageable
- Did you find the virtual environment lame/exciting
- Did you find the virtual environment amateurish/professional
- Did you find the virtual environment gaudy/classy
- Did you find the virtual environment unpresentable/presentable
- Did you find the virtual environment ugly/beautiful
- Did you find the virtual environment disagreeable/likeable

Experience Consequence
- I suffered from fatigue.
- I suffered from headache.
- I suffered from eyestrain.
- I felt an increase of my salivation during my interactions.
- I suffered from nausea during my interactions.
- I suffered from heaviness in my head during my interactions.
- I suffered from dizziness during my interactions.
- I suffered from vertigo during my interactions.

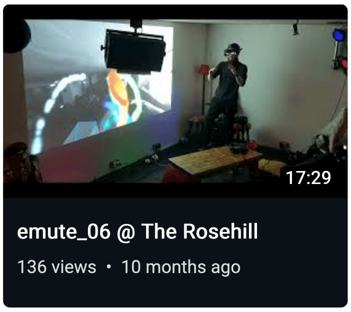
Technology Adoption
- If I use again the same virtual environment, my interaction with the environment would be clear and understandable for me.
- It would be easy for me to become skillful at using the virtual environment.
- Learning to operate the virtual environment would be easy for me.
- Using the interaction devices (headset and headphones) is a bad idea.
- The interaction devices (headset and headphones) would make audiovisual art more interesting.
- I would like to work with the interaction devices (headset and headphones).
- I have the resources necessary to use the interaction devices (headset and headphones).

C polygons~ Archive

C.1 polygons~ Related Media



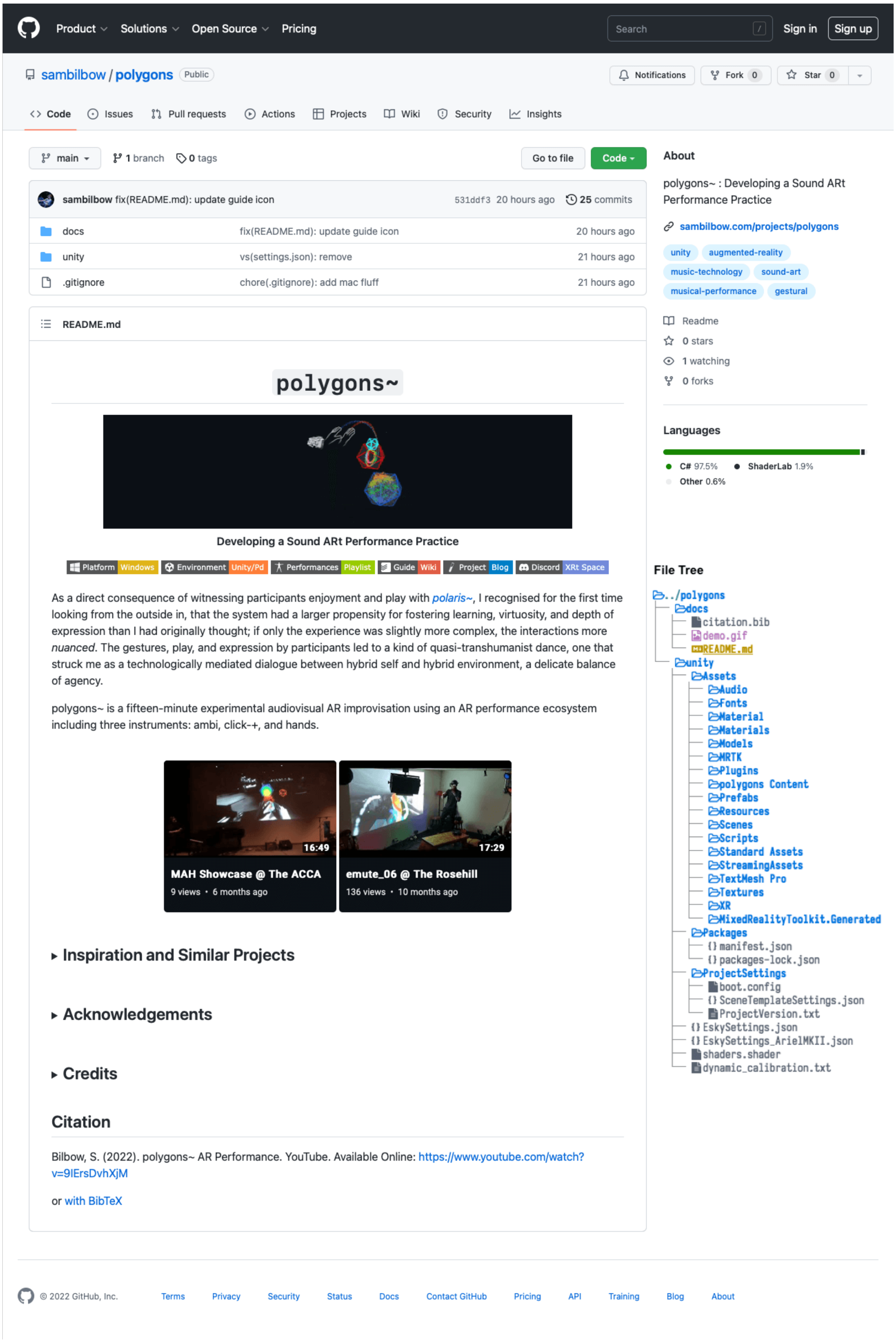
youtu.be/zOeXI_WvzJA



youtu.be/9IErsDvhXjM

polygons~ Video Recordings

C.2 polygons~ Code Repository



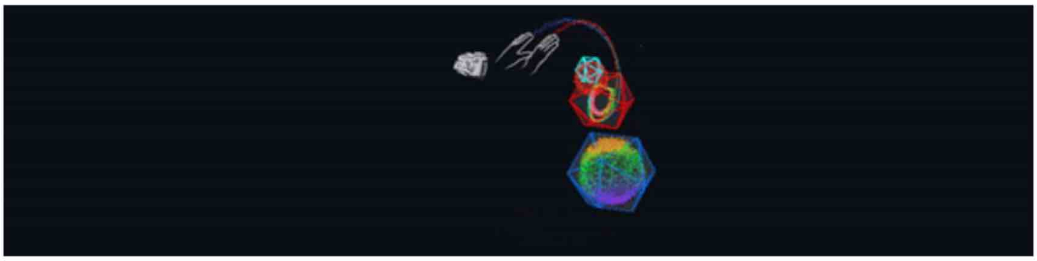
github.com/sambilbow/polygons
polygons~ on GitHub with file tree

C.3 polygons~ Blog Contents

C.3.1 Summary

polygons~

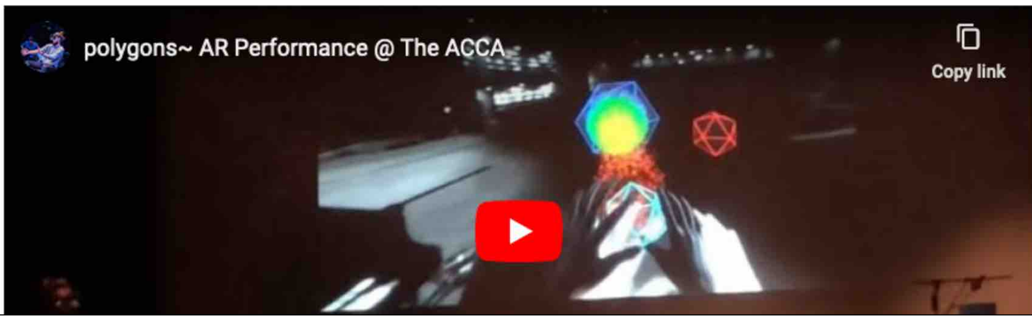
Project Files



Summary

As a direct consequence of witnessing participants enjoyment and play with polaris~, I recognised for the first time looking from the outside in, that the system had a larger propensity for fostering learning, virtuosity, and depth of expression than I had originally thought; if only the experience was slightly more complex, the interactions more nuanced. The gestures, play, and expression by participants led to a kind of quasi-transhumanist dance, one that struck me as a technologically mediated dialogue between hybrid self and hybrid environment, a delicate balance of agency.

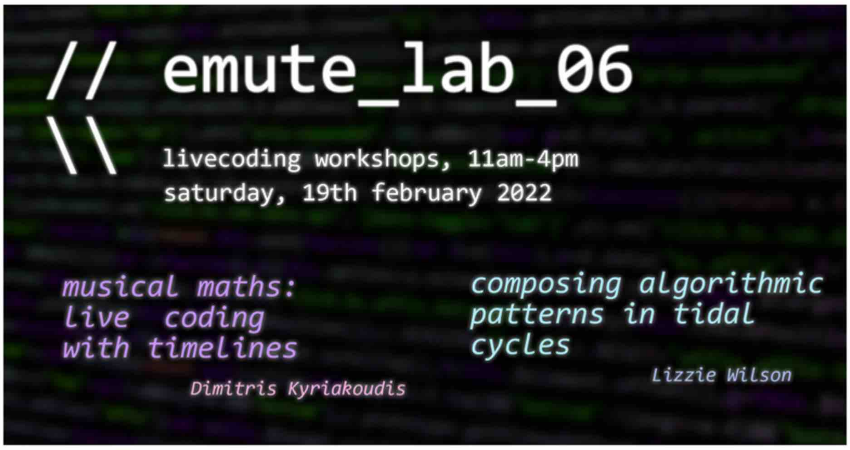
polygons~ is a fifteen-minute experimental audiovisual AR improvisation using an AR performance ecosystem including three instruments: ambi, click-+, and hands.



C.3.2 emute Lab Blog

Livecoding Workshops

11:00 - 16:00



Facebook Event
Tickets: £7 or £4 (concession/student) https://www.ticketsource.co.uk/emute-lab/emute-lab-6-livecoding-workshops/e-pyammo

During these workshops, two of the performers will introduce the practice of live coding music. They will explain how their live coding instruments of choice work (the very same instruments that they will use to perform later in the evening), guide participants through a hands-on session of play and experimentation, and discuss their personal artistic practices and approaches to performing improvised music by writing and modifying computer code, live on stage. No prior coding experience is required, just the curiosity to learn (+ a laptop and a pair of headphones).

Dimitris Kyriakoudis - Musical Maths: Live Coding Music with TimeLines

A gentle introduction to live coding music using TimeLines, a free & open source modular synthesiser and sequencer, presented by its developer.

Participants will learn about live coding and sound synthesis, explore the meaning of the oftentimes confusing phrase "music is maths", and discover how to use primary school-level maths to recreate compositional techniques used by both children's folk songs and J.S. Bach alike, but in the context of modern music.

No previous musical or coding experience required. In order to follow along you will need a laptop using Windows, Mac OS, or most flavours of Linux, as well as a pair of headphones. Participants are encouraged to attempt installing the software in preparation for the workshop (following the instructions in the link above), but can also get help with the installation process during the workshop.

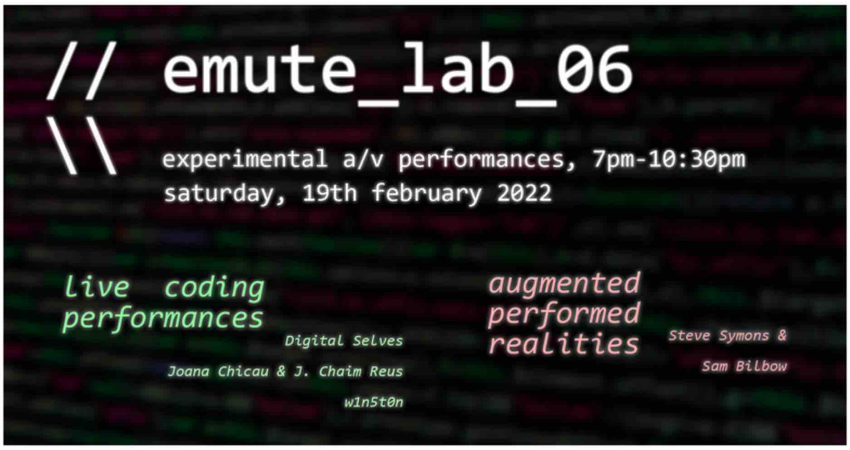
Lizzie Wilson - Composing Algorithmic Patterns in Tidal Cycles

In this workshop, participants will be learning the fundamental principles of live coding. In live coding, computer language is the primary medium for notation and describing the rules with which to synthesise artworks, in this case we consider the case where the output is musical pattern. Participants will be composing patterns algorithmically with the Tidal Cycles software: a language for describing flexible (e.g. polyphonic, polyrhythmic, generative) sequences of sounds, notes, parameters, and all kind of information. Tidal Cycles (or 'Tidal' for short) is free/open source software written using the functional programming language Haskell, that utilises the audio capabilities of the SuperCollider software. It includes simple and flexible notation for rhythmic sequences, and an extensive library of patterning functions for combining and transforming them. This allows you to quickly create complex patterns from simple ingredients. Learning the strategies used by live coders to create complex and varied outcomes from simple code structures is the workshops main outcome. No previous coding or musical experience required.

Participants should bring a laptop and headphones to the workshop. If they feel comfortable doing so, they should download the TidalCycles software onto their laptop BEFORE the workshop (see tidalcycles.org/docs/getting-started/). If not, they will be able to participate in the workshop, provided they are able to access the internet through their laptop (WiFi connection will be provided).

Experimental A/V Performances

19:00 - 22:30



Facebook Event
Tickets: £7 or £4 (concession/student)

Digital Selves

@dgtlselves

In this performance, live coder digital selves will explore the human-machine creative relationship. The live coder will work in conjunction with, and sometimes against, a machine agent that creates its own pattens of code. Through performance, a co-creative system emerges, using the machine agent to explore not-yet conceptualised code sequences. This forms part of a wider context of research which centres around co-creative systems of algorithmic composition based on models of affective response (emotion). Please be aware that this performance will be filmed.

Bio:
digital selves is a London-based computer musician who uses algorithms of synthesis and samples to create improvised, crunchy sounds and melodic texture. They have performed at various events in the UK and internationally and use the programming mini-language TidalCycles to create algorithmic music that recontextualises club culture, experimental art and human-computer interaction.

Joana Chicau and J. Chaim Reus

@bchicau

@_jchaim

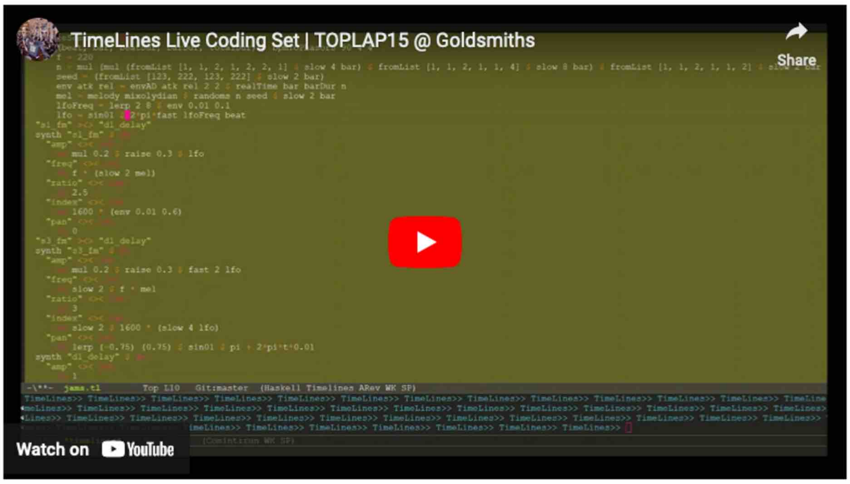
'Web Choreographies' is an assemblage of live coded visual experiments performed in the web browser. This performance is part of an on-going research on how design and web based computational systems can be used to construct new scenarios, imaginaries and hypotheses guided by choreographic concepts. By privileging open source tools and investigation through feminist lens, Joana Chicau combines real-time algorithmic composition and movement studies to rethink the vocabularies, protocols, modes of participation and conditions for the affective interfacing of bodies and technologies.

Bios: Joana Chicau is a designer and researcher — with a background in dance. She researches the intersection of the body with the designed and programmed environment, aiming at widening the ways in which digital sciences is presented and made accessible to the public. The latter informs a practice and exploration of various forms and formats — interweaving web programming with choreography — from the making of online platforms to performances and workshops.
She has been participating and co-organizing events involving collaborative coding, algorithmic improvisation, open discussions on digital equity and activism. Chicau is a member of the collective Varia.zone and a lecturer at the University of Arts of London.

J. Chaim Reus is a Dutch-American research-composer, born in New York and thereafter living in Amsterdam and then Florida, where he became involved in the American folk-art scene. Years later he moved to the Netherlands where he developed a uniquely intimate live practice cutting across disciplines of music and visual art, science and digital culture. jonathanreus.com

w1n5t0n

@lm_w1n5t0n



w1n5t0n is one of Infinite Monkeys. His species has developed sufficient intelligence to enable the use of tools and instruments, but not enough to actually understand how most of them work, so he often resorts to making his own. To this end he reimagines recycles, and reappropriates anything he can find laying around the jungle, from leftover temporally functional-reactive homoiconic metaprogramming to nice sticks and pretty pebbles – all ethically and open sourced, of course. In doing so he explores the intersection of music, art, mathematics, programming, randomness, improvisation, internet memes, infinity, algorithmocomputational creativity, The Meaning of Life™, and fun.

Bio: When not dwelling on trees (either the plain ones or the Abstract Syntax kind), w1n5t0n transmorphs to Dimitris Kyriakoudis and wears clothes and drinks tea and says "please" and "thank you" and pays bills and taxes. He can be usually found researching HCI and experimenting with live coding instrument design at the University of Sussex.

Steve Symons and Sam Bilbow

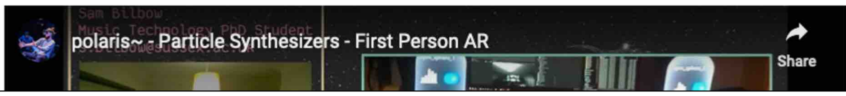
Steve and Sam will improvise using their experimental virtual musical interfaces, accessed by a Gametrak and an Augmented Reality Headset. The performance examines three-dimensional bodily motion, and how these interfaces might relate to one another, both comparing and contrasting their sonic palettes and gestures.

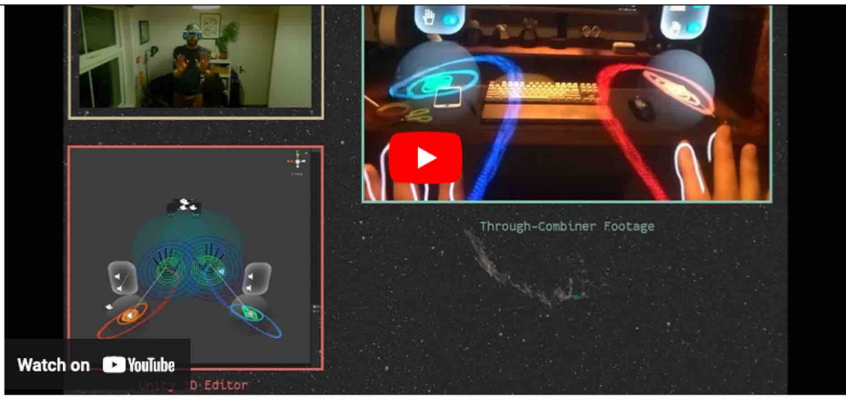
@stevemuio

Steve Symons has spent many years making embedded locative audio systems and making / improvising music with NIMEs. He is interested in enactive interfaces, woodwork and finding new metaphors for collaborative instruments.

@sambilbow

Sam is a Doctoral Researcher at Sussex working with augmented reality as a medium for gestural and musical expression. His work uses DIY and open-source hardware to create real-time and combined real / virtual performances of space. Below is a demonstration of the system he will be performing with.





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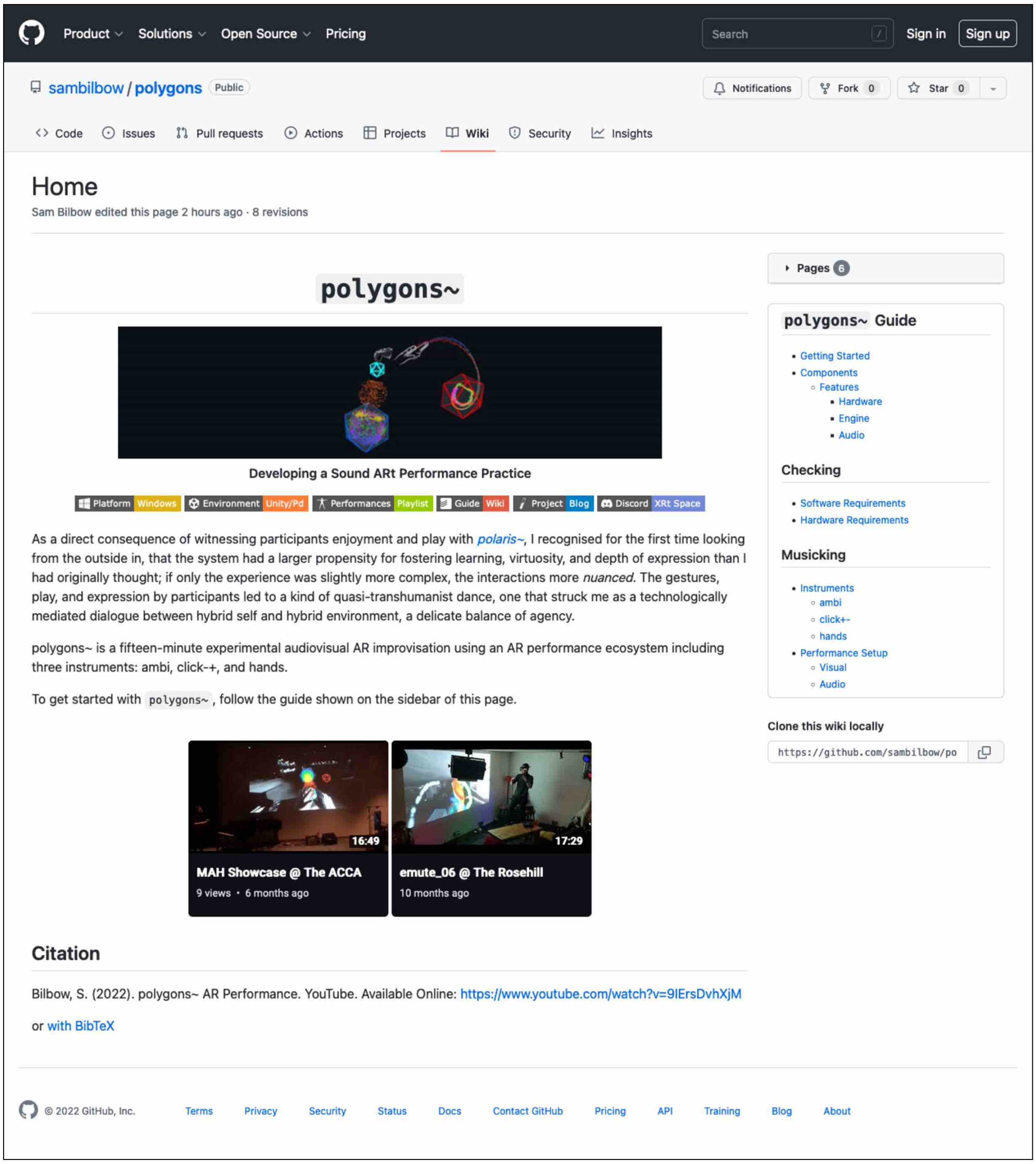

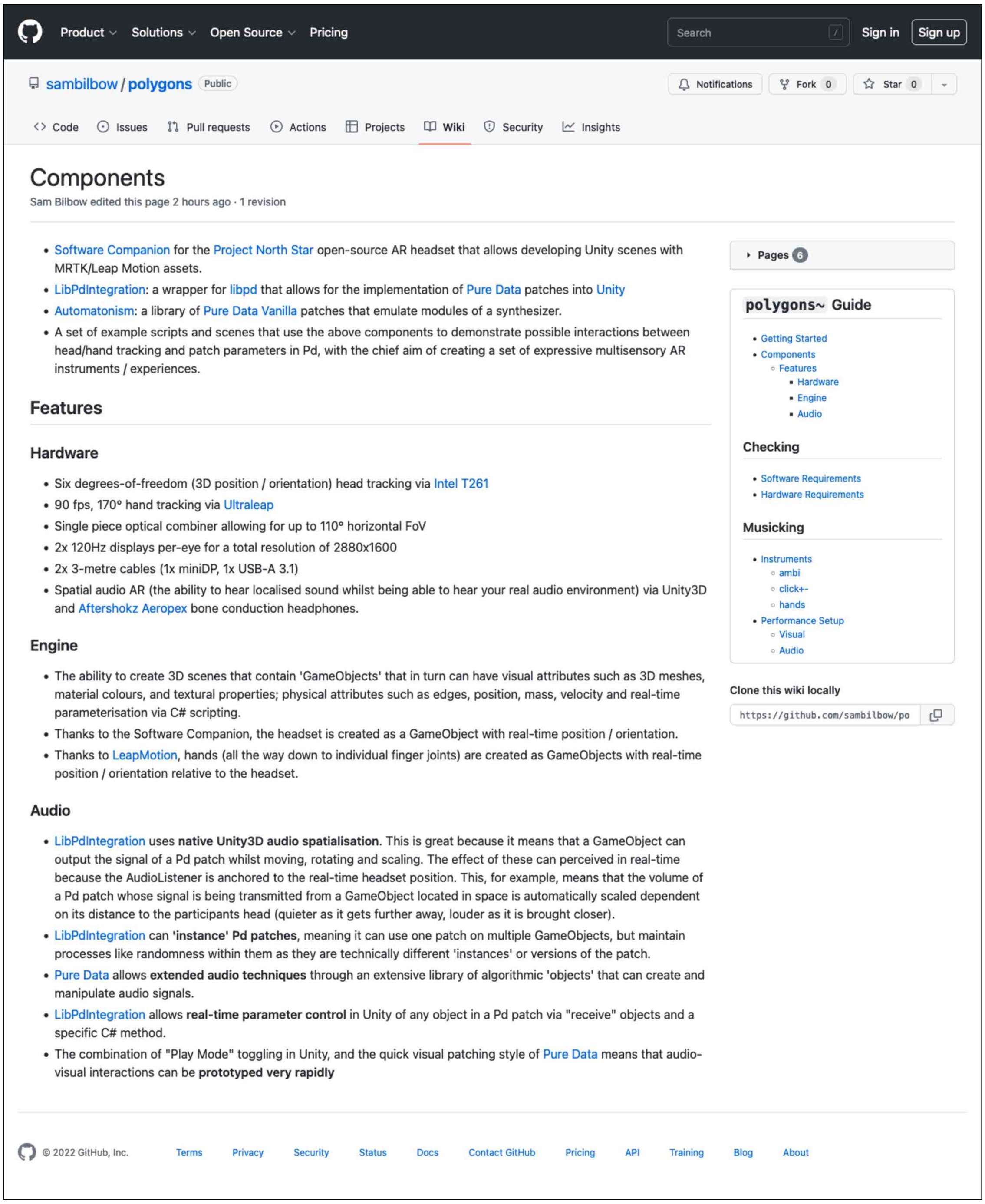

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Components

Sam Bilbow edited this page 2 hours ago · 1 revision

- Software Companion for the Project North Star open-source AR headset that allows developing Unity scenes with MRTK/Leap Motion assets.
- LibPdIntegration: a wrapper for libpd that allows for the implementation of Pure Data patches into Unity
- Automatonism: a library of Pure Data Vanilla patches that emulate modules of a synthesizer.
- A set of example scripts and scenes that use the above components to demonstrate possible interactions between head/hand tracking and patch parameters in Pd, with the chief aim of creating a set of expressive multisensory AR instruments / experiences.

Features

Hardware

- Six degrees-of-freedom (3D position / orientation) head tracking via Intel T261
- 90 fps, 170° hand tracking via Ultraleap
- Single piece optical combiner allowing for up to 110° horizontal FoV
- 2x 120Hz displays per-eye for a total resolution of 2880x1600
- 2x 3-metre cables (1x miniDP, 1x USB-A 3.1)
- Spatial audio AR (the ability to hear localised sound whilst being able to hear your real audio environment) via Unity3D and Aftershokz Aeropex bone conduction headphones.

Engine

- The ability to create 3D scenes that contain 'GameObjects' that in turn can have visual attributes such as 3D meshes, material colours, and textural properties; physical attributes such as edges, position, mass, velocity and real-time parameterisation via C# scripting.
- Thanks to the Software Companion, the headset is created as a GameObject with real-time position / orientation.
- Thanks to LeapMotion, hands (all the way down to individual finger joints) are created as GameObjects with real-time position / orientation relative to the headset.

Audio

- LibPdIntegration uses **native Unity3D audio spatialisation**. This is great because it means that a GameObject can output the signal of a Pd patch whilst moving, rotating and scaling. The effect of these can perceived in real-time because the AudioListener is anchored to the real-time headset position. This, for example, means that the volume of a Pd patch whose signal is being transmitted from a GameObject located in space is automatically scaled dependent on its distance to the participants head (quieter as it gets further away, louder as it is brought closer).
- LibPdIntegration can **'instance' Pd patches**, meaning it can use one patch on multiple GameObjects, but maintain processes like randomness within them as they are technically different 'instances' or versions of the patch.
- Pure Data allows **extended audio techniques** through an extensive library of algorithmic 'objects' that can create and manipulate audio signals.
- LibPdIntegration allows **real-time parameter control** in Unity of any object in a Pd patch via "receive" objects and a specific C# method.
- The combination of "Play Mode" toggling in Unity, and the quick visual patching style of Pure Data means that audio-visual interactions can be **prototyped very rapidly**

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`https://github.com/sambilbow/po`

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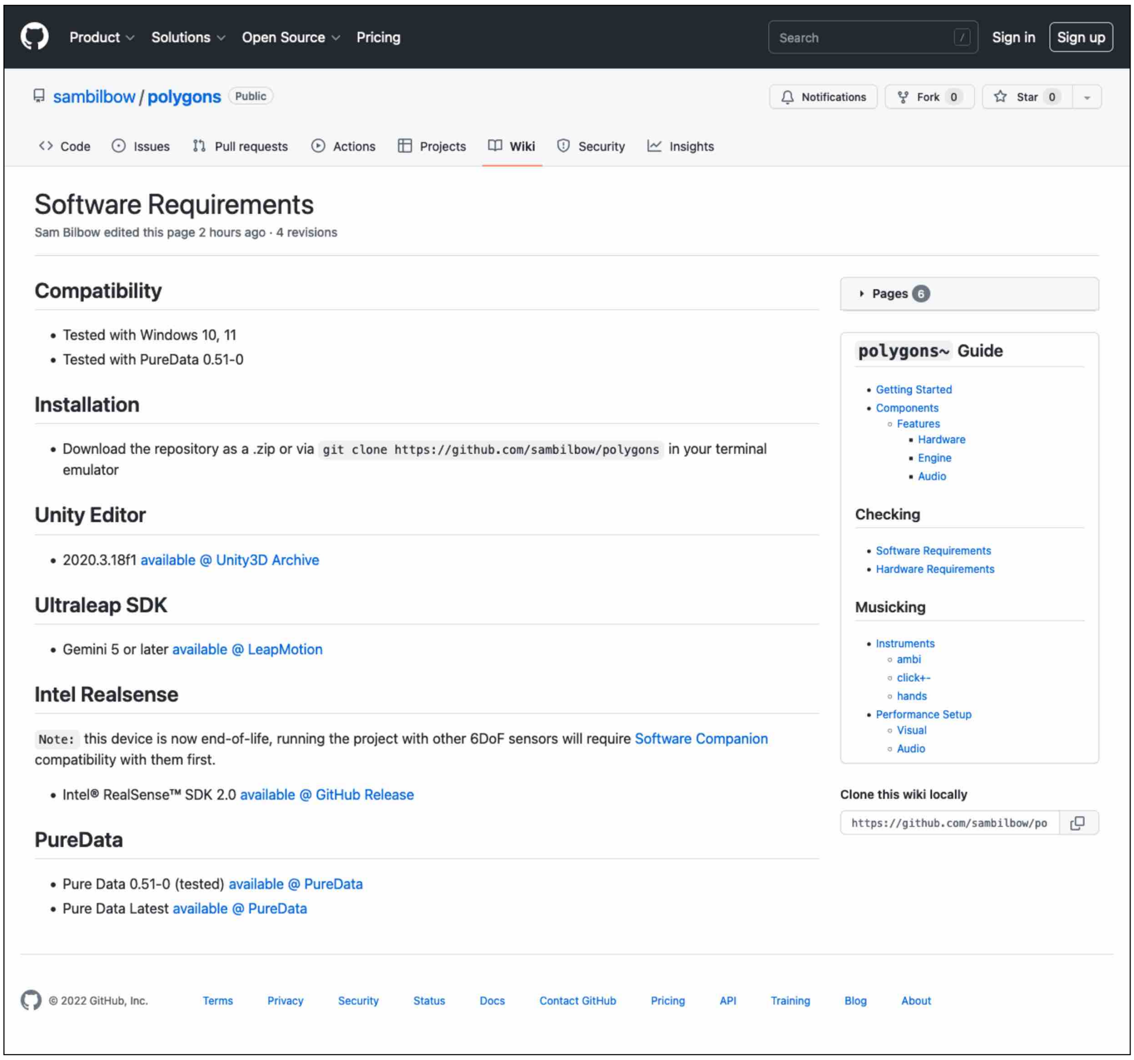
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Compatibility
• Tested with Windows 10, 11
• Tested with PureData 0.51-0
Installation
• Download the repository as a .zip or via git clone https://github.com/sambilbow/polygons in your terminal emulator
Unity Editor
• 2020.3.18f1 available @ Unity3D Archive
Ultraleap SDK
• Gemini 5 or later available @ LeapMotion
Intel Realsense
Note: this device is now end-of-life, running the project with other 6DoF sensors will require Software Companion compatibility with them first.
• Intel® RealSense™ SDK 2.0 available @ GitHub Release
PureData
• Pure Data 0.51-0 (tested) available @ PureData
• Pure Data Latest available @ PureData
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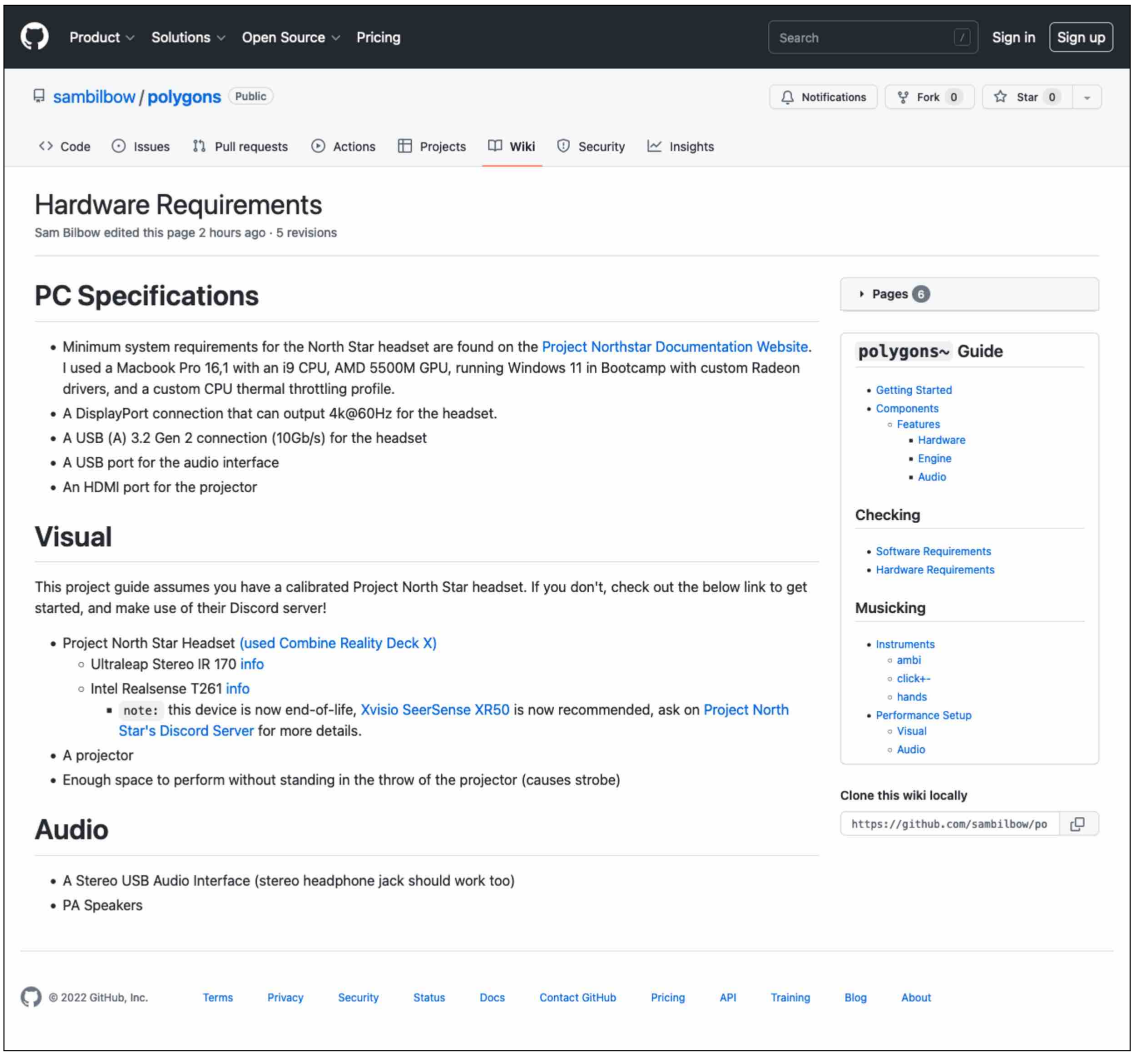

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Hardware Requirements

Sam Bilbow edited this page 2 hours ago · 5 revisions

PC Specifications

- Minimum system requirements for the North Star headset are found on the Project Northstar Documentation Website. I used a Macbook Pro 16,1 with an i9 CPU, AMD 5500M GPU, running Windows 11 in Bootcamp with custom Radeon drivers, and a custom CPU thermal throttling profile.
- A DisplayPort connection that can output 4k@60Hz for the headset.
- A USB (A) 3.2 Gen 2 connection (10Gb/s) for the headset
- A USB port for the audio interface
- An HDMI port for the projector

Visual

This project guide assumes you have a calibrated Project North Star headset. If you don't, check out the below link to get started, and make use of their Discord server!

- Project North Star Headset (used Combine Reality Deck X)
  - Ultraleap Stereo IR 170 info
  - Intel Realsense T261 info
    - `note:` this device is now end-of-life, Xvisio SeerSense XR50 is now recommended, ask on Project North Star's Discord Server for more details.
- A projector
- Enough space to perform without standing in the throw of the projector (causes strobe)

Audio

- A Stereo USB Audio Interface (stereo headphone jack should work too)
- PA Speakers

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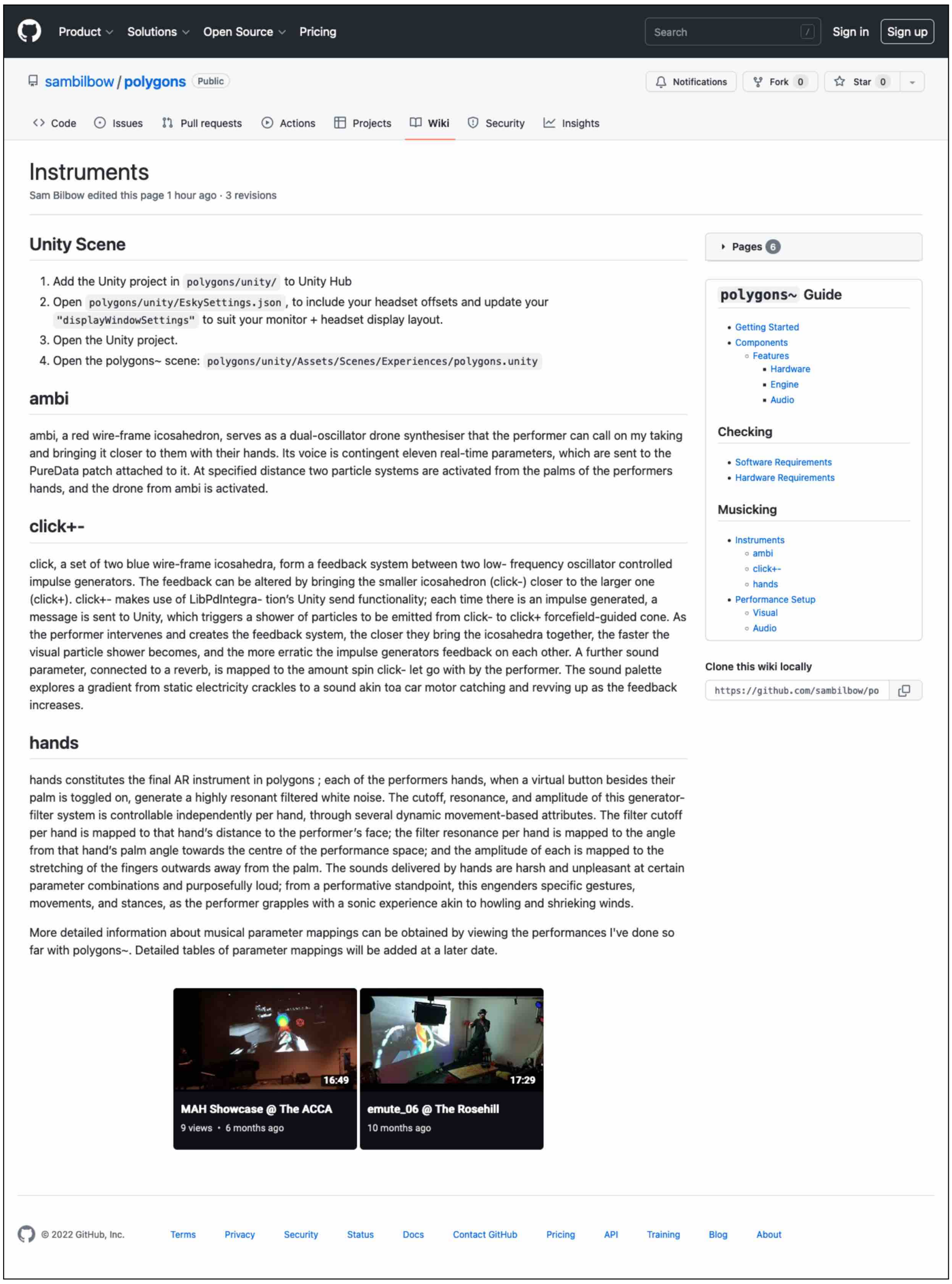

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Instruments

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Unity Scene

1. Add the Unity project in `polygons/unity/` to Unity Hub
2. Open `polygons/unity/EskySettings.json`, to include your headset offsets and update your `"displayWindowSettings"` to suit your monitor + headset display layout.
3. Open the Unity project.
4. Open the polygons~ scene: `polygons/unity/Assets/Scenes/Experiences/polygons.unity`

ambi

ambi, a red wire-frame icosahedron, serves as a dual-oscillator drone synthesiser that the performer can call on my taking and bringing it closer to them with their hands. Its voice is contingent eleven real-time parameters, which are sent to the PureData patch attached to it. At specified distance two particle systems are activated from the palms of the performers hands, and the drone from ambi is activated.

click+-

click, a set of two blue wire-frame icosahedra, form a feedback system between two low- frequency oscillator controlled impulse generators. The feedback can be altered by bringing the smaller icosahedron (click-) closer to the larger one (click+). click+- makes use of LibPdIntegra- tion's Unity send functionality; each time there is an impulse generated, a message is sent to Unity, which triggers a shower of particles to be emitted from click- to click+ forcefield-guided cone. As the performer intervenes and creates the feedback system, the closer they bring the icosahedra together, the faster the visual particle shower becomes, and the more erratic the impulse generators feedback on each other. A further sound parameter, connected to a reverb, is mapped to the amount spin click- let go with by the performer. The sound palette explores a gradient from static electricity crackles to a sound akin toa car motor catching and revving up as the feedback increases.

hands

hands constitutes the final AR instrument in polygons ; each of the performers hands, when a virtual button besides their palm is toggled on, generate a highly resonant filtered white noise. The cutoff, resonance, and amplitude of this generator-filter system is controllable independently per hand, through several dynamic movement-based attributes. The filter cutoff per hand is mapped to that hand's distance to the performer's face; the filter resonance per hand is mapped to the angle from that hand's palm angle towards the centre of the performance space; and the amplitude of each is mapped to the stretching of the fingers outwards away from the palm. The sounds delivered by hands are harsh and unpleasant at certain parameter combinations and purposefully loud; from a performative standpoint, this engenders specific gestures, movements, and stances, as the performer grapples with a sonic experience akin to howling and shrieking winds.

More detailed information about musical parameter mappings can be obtained by viewing the performances I've done so far with polygons~. Detailed tables of parameter mappings will be added at a later date.

16:49
MAH Showcase @ The ACCA
9 views • 6 months ago

17:29
emute_06 @ The Rosehill
10 months ago

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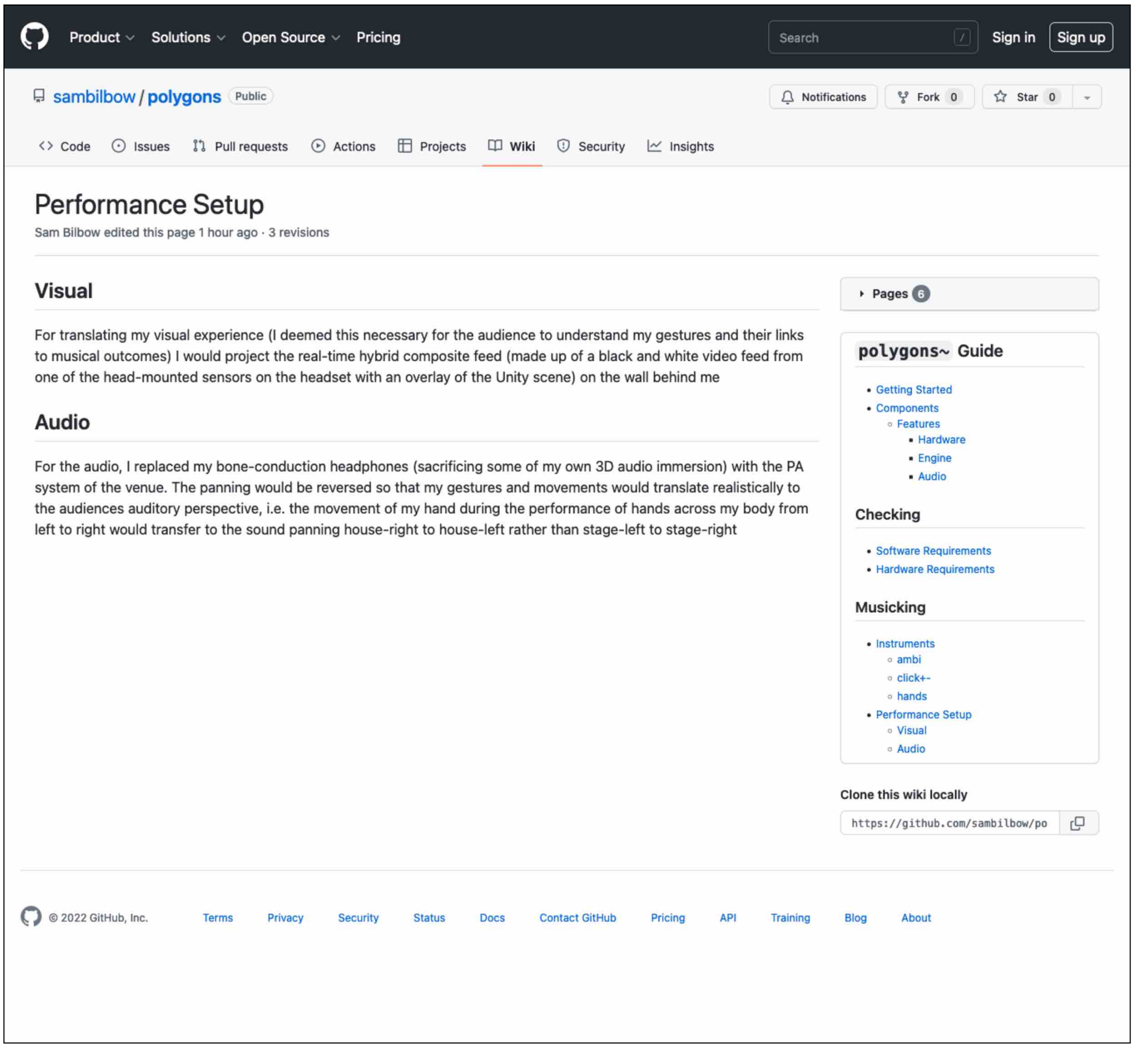
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Visual
For translating my visual experience (I deemed this necessary for the audience to understand my gestures and their links to musical outcomes) I would project the real-time hybrid composite feed (made up of a black and white video feed from one of the head-mounted sensors on the headset with an overlay of the Unity scene) on the wall behind me
Audio
For the audio, I replaced my bone-conduction headphones (sacrificing some of my own 3D audio immersion) with the PA system of the venue. The panning would be reversed so that my gestures and movements would translate realistically to the audiences auditory perspective, i.e. the movement of my hand during the performance of hands across my body from left to right would transfer to the sound panning house-right to house-left rather than stage-left to stage-right
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