Sonification of Brain Activity Using EEG for an Audio-Reactive Installation

To what extent can an audio-reactive system driven by EEG signals create a meaningful representation of a user's emotional states, and how does this impact the user's subjective experience of emotion?

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11. Project Overview

This project explores the intersection of brain-computer interfaces (BCI) and generative music, aiming to create an audio-reactive system that converts neural activity detected from an EEG headset into a dynamic musical interface. The goal is to develop an interactive musical installation where a participant's real-time brain activity directly influences a musical composition. Drawing from research on electroencephalography (EEG) and brainwave analysis, this project investigates how sound and music modulate brain activity and emotional states, offering both artistic and scientific insights into neurofeedback-driven music generation.

Studies on musical emotions reveal that music engages neural circuits associated with pleasure, motivation, and emotional processing, particularly within the limbic system. Pleasant and unpleasant sounds engage with different areas of the human cortex, generating responses influenced by personal characteristics. Whether some music or a sound is enjoyable also depends on the audience's culture, age and musical experience (Gaser, 2003, p. 1). Familiarity with a piece of music also plays a key role in influencing emotional responses, as familiar music activates reward-related brain regions more intensely than unfamiliar music. Additionally, EEG research supports the asymmetry hypothesis, suggesting that positive emotions are predominantly processed in the left frontal cortex, while negative emotions are more lateralised to the right hemisphere (Almudena, 2021, p. 3).

Understanding these neural mechanisms is critical to designing an EEG-driven generative music system that can accurately reflect the emotional states of its users.
These profound findings emphasise the core question of this project.
The primary hypothesis guiding this research is that specific patterns of neural activity, which correlate with distinct emotional and cognitive states, can be meaningfully expressed through generative soundscapes. By mapping real-time EEG data to a generative music engine, the system will allow users to experience music as a reflection of their own mental state, opening up possibilities for applications in music therapy, immersive art installations, and neuroscientific research. EEG has become an essential tool for studying the neural basis of musical

affect, and another interesting case of study arises from these reflections. What is the role of sound and music in modulating brain activity and emotional states of a user? This work seeks to deepen our understanding of how music influences cognition and emotion, while also exploring new forms of interactive, brain-driven musical experiences.

12. Background history and research

Biosignals and EEG – Electroencephalography

Electrical signals generated in the human body were first identified in 1840 by Emil Heinrich du Bois-Reymond from human muscles. For nearly two centuries, the electrical nature of life has been well established. Research in the field has continued ever since, leading to significant advancements in the detection and usage of these biosignals. One of the most intriguing developments in recent decades has been the emergence of technological interfaces designed to interact with such signals. A biosignal interface bridges biology and technology, harnessing electrical activity from the brain, muscles, and nerves to control and communicate with external systems. These signals are measured using electrodes, amplifiers, and computational methods to extract meaningful patterns. By capturing and analysing biosignals, modern systems enable applications ranging from medical diagnostics to creative fields like music, where they translate physiological states into dynamic outputs (Miranda, 2006, p. 173).

Electroencephalography (EEG) is a method for measuring brain activity by detecting the electrical signals generated by cortical neurons. These signals, originating from millions of neurons firing, create minute voltage fluctuations on the scalp that can be captured by electrodes placed in specific configurations. Typically, EEG electrodes are arranged in the internationally standardised 10-20 system, strategically positioned to record electrical activity from various brain regions. The collected signals are then amplified, filtered and processed using techniques like Fourier transforms or machine learning algorithms to extract meaningful features while removing noise (Miranda, 2006, p. 174). The measured data is often associated with different mental states. The frequency variations of these electric fields are usually categorised into five specific bands that reflect such states:

Delta waves (0.5-4 Hz) – Deep sleep and unconscious processing
Theta waves (4-8 Hz) – Drowsiness, relaxation and meditation
Alpha waves (8-13 Hz) – Relaxed wakefulness, creativity
Beta waves (13-30 Hz) – Active thinking and concentration
Gamma waves (>30 Hz) – Stress or high cognitive load
(Miranda, 2006, p. 184)

As a non-invasive method, EEG has been extensively used in clinical and experimental settings. It has applications in neurology, cognitive research, and even brain-computer interfaces (BCIs).

Brain-computer Interfaces and Brain Music History

Brain-computer Interfaces (BCIs) have a history that dates back to the mid-20th century and is deeply rooted in neuroscience and human-machine interaction. Initially developed for medical and assistive purposes, BCIs emerged from early electroencephalography (EEG) research in the 1920s and became a focal point of innovation in the 1970s, when researchers began to explore how brain signals could be used to control external devices. Over time, computing power and signal processing advancements led to more sophisticated BCIs, expanding their applications beyond clinical settings into creative domains, including music and sound design.

The exploration of brain-controlled music dates back to the late 20th century, when scientists and artists began experimenting with how EEG signals could influence sound generation. One of the pioneering projects in this space was *Brainwave Music* by composer and researcher David Rosenboom in the 1970s. Rosenboom's work demonstrated how EEG data could be mapped to musical parameters, allowing performers to shape sound using their brain activity. Another early effort was Alvin Lucier's *Music for Solo Performer* (1965). EEG signals were used to translate alpha waves from the performer's brain into vibrations that activated percussion instruments, creating an experimental musical experience (Straebel, 2014, p. 17). Richard Teitelbaum also expanded on these ideas in works like *Organ Music* (1968) and *In Tune* (1968), incorporating not only EEG but also heartbeat and breath

sounds to influence electronic soundscapes. His approach emphasised the body's physiological rhythms as direct compositional elements, contributing to the broader field of live electronic and interactive music performance (Rosenboom, 1990, p. 48).

BCI in Music – Innovations and Future Possibilities

As technology progressed into the 21st century, new projects that refined and expanded the use of BCIs in music emerged. In 2009, *Brain Computer Interface and Music* (BCMI), led by Eduardo Miranda at Plymouth University, developed systems that allowed users to generate music in real time using brain activity. The BCMI project pioneered applications for disabled musicians, offering individuals with severe motor impairments the ability to compose and perform music using thought alone (Eaton, 2013, p. 15). Similarly, *Encephalophone*, developed at the University of Washington in 2017, enabled users to control musical instruments through brain signals, creating new avenues for musical expression, again, particularly for those with limited physical movement (Deuel, 2017, p. 11).

Recent BCI music applications have also found their way into live performances and experimental sound design. For example, the *Brain-Body Digital Musical Instrument* (BBDMI) is a currently developing research project by Atau Tanaka et al., aimed at creating a digital musical instrument that integrates physiological signals from the brain (EEG) and muscles (EMG) for musical performance and interaction. Open-source platforms such as EEGsynth or EAVI Exg allow the acquisition and processing of EMG and EEG signals in real-time, which performers can use to control sound and music (2023).

Today, BCIs continue to push the boundaries of musical creativity, offering artists and researchers innovative ways to integrate biofeedback with sound, composition, and performance. These developments provide new forms of artistic expression, exploring embodied interaction and new forms of digital performance. As technology advances, the future of music may increasingly be shaped by the direct connection between the mind and sound; the evolution of biosignal music challenges traditional boundaries between performer, instrument, and audience, paving the way for novel forms of musical interaction.

13. Context, Audience and Goals

This project exists at the intersection of neuroscience, generative music, and interactive installations. Its central context lies within immersive sensory experiences and experimental sound design, drawing upon brain-computer interfaces (BCIs) and EEG signal processing developments. The work is presented as a real-time, audio-reactive installation, situated within gallery spaces or technological art exhibitions, such as the EMCT(Electronic Music and Computing Technologies)/Creative Computing Degree Show 2025, where it was first showcased. The main goal is to enable participants to explore their mental states through sound, allowing their emotions to shape an evolving musical environment simply by wearing an EEG headset. This connection creates a deeply personal and introspective experience, particularly intriguing in terms of feedback loops—where not only is the participant's brain activity represented, but the generated output also influences their state of mind, thereby modulating the sonic output in real-time.

The core technology employed—a wearable EEG headset—streams real-time brainwave data into a Max/MSP-based audio system. This raw neural data is then translated into a generative musical environment through a combination of mapping, sound synthesis and audio processing. The installation thus acts as a bridge between the inner activity of the human brain and the external sonic environment, enabling users to "hear" their brain state. The ideal audience for this project includes both general visitors to immersive exhibitions and individuals with specific interests in digital art, neurofeedback, cognitive science, and music technology. Furthermore, the system is designed to be accessible even to those unfamiliar with EEG technology. It offers immediate visual feedback and relative sonic changes that reflect shifts in mental state, facilitating engagement through visual and audio.

Within the scope of interactive installations, this project is experienced rather than used in a utilitarian sense. Its success is thus measured through audience perception and emotional impact. A major goal was to create a system where users could feel a personal connection between their internal emotional or cognitive state and the evolving audio landscape. To this end, the project builds on the legacy of

pioneering works in EEG music, such as David Rosenboom's "Brainwave Music" and Alvin Lucier's "Music for Solo Performer," while advancing these ideas using modern BCI technology and digital signal processing.

The installation achieves this effect by mapping five mental states—Delta, Theta, Alpha, Beta, and Gamma—onto distinct sound "moods." These soundscapes are artistically arbitrary but grounded in neuroscience and psychoacoustics. For instance, Delta waves (linked with deep sleep) produce low-frequency sub-bass tones, while Beta and Gamma waves (associated with concentration and high cognitive load) correspond to more complex, fast-paced, and dissonant sound patterns. This deliberate mapping allows the installation to convey meaningful emotional cues rather than generic ambient sound, reinforcing its testable hypothesis: that EEG patterns can be translated into perceptually distinct sonic representations of mental states.

From a usability standpoint, the goals are to provide a stable yet flexible system for real-time EEG-driven sound synthesis. Although the project was initially built to be used with an EEG headset (the Unicorn Hybrid Black), it incorporates simulated data streams and JavaScript-based processing to ensure the system remains active even when no headset is worn. This enables the installation to function continuously in a gallery environment without requiring constant user interaction. The project's goals are thus both experiential and functional. On the experiential side, it seeks to create an immersive environment where users can reflect on their internal states. On the functional side, it aims to create an effective and adaptable sonic experience that can be used by a wide range of visitors. While the project falls short in offering clinical-grade diagnostics, it suggests future possibilities for applications in experimental music or educational tools to explore neuroscience through art.

This dual ambition is echoed in the degree show users' feedback. A wide range of diverse participants noted that the system often felt "alive" and "in tune" with their energy or emotional state (Sonification of brain Activity Feedback, May 2025). Such reactions validate the design's foundational assumption: that individuals can perceive and interpret the sonic representation of their own brain activity, and that this perception can lead to a deeper sense of self-awareness or emotional resonance.

The goal was not to diagnose or prescribe, but to offer an experiential interface between mind and music—one that could eventually aspire to further interdisciplinary work in biosignal-based music and cognitive research.

In summary, the context of this project is firmly rooted in the evolving field of neuro-art installations. It addresses an audience that spans from the general public to academic researchers and artists, offering both an introspective and sensorial experience. The goals are to create a meaningful, interactive installation that reflects the user's mental state through sound, and to explore the potential of EEG signals as tools for creative expression.

14. Project in Depth

Introduction

The users of this interactive installation wear an 8-channel wearable EEG headset that streams real-time brainwave data to Max/MSP. This data is transmitted via UDP (User Datagram Protocol) to the Max/MSP environment, where it is further processed and mapped to multiple parameters across the sound sections, enabling real-time manipulation of a dynamic and reactive soundscape.

The core of the mapping system revolves around detecting the current user's mental state—Delta, Theta, Alpha, Beta, and Gamma—based on a weighted comparison between the bandpowers recorded by the EEG headset. The project is designed to map these five mental states into distinct sonic "moods" that reflect the user's brain activity. As outlined earlier in the Biosignals and EEG section (Chapter 2), each frequency range is associated with different cognitive and emotional states. To facilitate a smooth transition between these mental states, a signal ramp is generated that linearly moves between five values: 0 for Theta, 25 for Delta, 50 for Alpha, 75 for Beta and 100 for Gamma. This ramp dynamically controls the interpolation between presets that shape the different moods. Whenever a change in mental state is detected, a new ramp is generated that starts from the current value and moves toward the new state, enabling a smooth transition in the sound experience.

This linear signal influences the volume of the different sound sections, the overall tempo, the tuning of the soundscape, plus various specific parameters of the sound synthesis. As the detected mental state moves into higher frequency ranges (Beta, Gamma), the system increases the tempo and pitch of the central frequency, creating a sense of growing mental engagement or stress.
The individual averaged band power values from the headset are used to control various parameters and effects across different audio sections, ensuring that the experience feels reactive and responsive to sudden changes in the signal.

Data Processing and EEG Simulator

The signal received from the EEG headset consists of a stream of 70 values. Seven band frequencies for each of the eight electrodes (Delta 1-8, Theta 9-16, Alpha 17-24, Beta Low 25-32, Beta Mid 33-40, Beta High 41-48, Gamma 49-56). Additionally, channels 57–63 provide the average across all eight electrodes for each frequency band, and channels 64–70 provide bipolar derivations for each frequency band, giving a more nuanced view of brain activity across multiple electrode locations.

EEG data structure (Table 1)

Index Number	Data Type	Frequency Band	Description
1-8	Individual Electrodes	Delta	Signal from each electrode (1-8) in the Delta band
9-16	Individual Electrodes	Theta	Signal from each electrode (1-8) in the Theta band
17-24	Individual Electrodes	Alpha	Signal from each electrode (1-8) in the Alpha band
25-32	Individual Electrodes	Beta Low	Signal from each electrode (1-8) in the Beta Low band
33-40	Individual Electrodes	Beta Mid	Signal from each electrode (1-8) in the Beta Mid band
41-48	Individual Electrodes	Beta High	Signal from each electrode (1-8) in the Beta High band
49-56	Individual Electrodes	Gamma	Signal from each electrode (1-8) in the Gamma band
57	Average	Delta	Average signal from all electrodes in the Delta band
58	Average	Theta	Average signal from all electrodes in the Theta band
59	Average	Alpha	Average signal from all electrodes in the Alpha band
60	Average	Beta Low	Average signal from all electrodes in the Beta Low band
61	Average	Beta Mid	Average signal from all electrodes in the Beta Mid band
62	Average	Beta High	Average signal from all electrodes in the Beta High band
63	Average	Gamma	Average signal from all electrodes in the Gamma band
64-70	Bipolar Derivation	Delta-Gamma	Bipolar derivations for each frequency band (Delta to Gamma)

A JavaScript subpatch is incorporated into the project to simulate EEG data by generating random values for each frequency band. This function was originally implemented to support the creative process, allowing for continuous sound generation without the need for the headset to be worn at all times. However, it was later integrated into the user experience to ensure a constantly evolving soundscape throughout the installation. This modification allows the soundscape to remain audible to visitors, even when no one is actively wearing the headset.

Another two JavaScript subpatches are also employed to extract individual data from the incoming lists: ChannelSplit.js and BandAverage.js. ChannelSplit separates the individual bandpower values and organises them by channel, enabling the visualisation of the eight channels. BandAverage extracts the average value of the seven bandpowers and redirects the result for both visualisation and mapping purposes.

EEG Mental State Detection

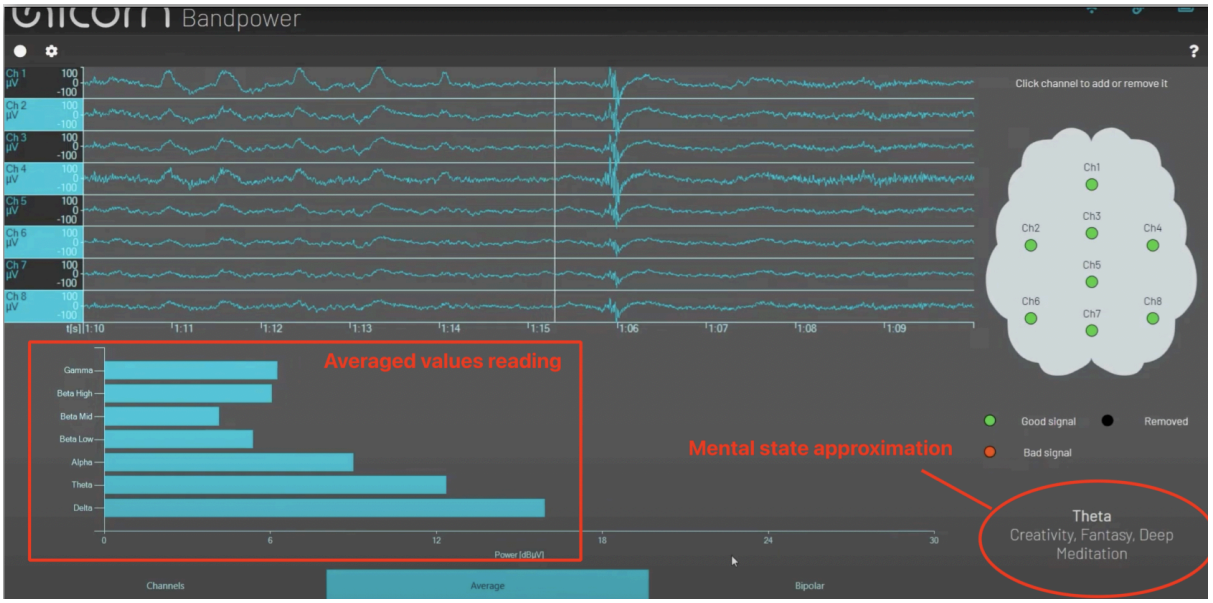
To obtain a meaningful reading of the user's mental state, a weighted comparison is required, as the highest bandpower value does not always accurately reflect the user's actual mental state. Lower frequency ranges, such as Delta and Theta, typically exhibit higher amplitude values compared to higher frequencies (Libenson, 2024, p. 6). If the individual bandpower values were compared directly as they are received, the system would consistently detect the Delta/Theta state. To address this, a weighted calibration system was implemented. In this system, adjacent bandpowers are multiplied by different factors and then summed together while subtracting the factorised opposite frequencies (See table 2).

The Unicorn Bandpower App, which operates similarly, displays the dominant mental state of the user while wearing the headset (See image 1); however, this data is not included in the UDP output of the software. However, EEG readings provide a broad measure of brain activity, usually with specific patterns linked to certain mental states under controlled conditions. These relationships are not one-to-one, and the overall EEG signal often lacks the precision needed for direct interpretation outside a lab setting. This challenge is akin to how muscle movements (e.g., frowning or smiling)

alone cannot definitively indicate mental state (e.g., anger or happiness) but can offer insights when contextualised. Consequently, mapping brainwaves to mental states can lead to overly simplistic or poorly controlled conclusions.

Nevertheless, this project does not aim to provide clinically accurate emotion detection but rather uses EEG data as a performative input to generate expressive soundscapes that resonate with mental states, and for the creative purposes of this project, this broad approximation provides an effective method for generating the relative soundscapes. Acknowledging the complexity of directly mapping mental states to brain activity, the EEGstate.js subpatch responsible for the comparison can be adjusted and personalised to more accurately reflect the user's emotional state (See table 2).

Unicorn Bandpower App interface (Image 1)



Initial weighting values (Table 2)

deltaScore	(0.3 * theta) + (0.3 * delta) - (0.4 * (betaLow + betaMid + betaHigh))
thetaScore	(0.5 * alpha) + (0.6 * theta) - (0.4 * (betaLow + betaMid + betaHigh + gamma))
alphaScore	(0.4 * betaLow) + (0.3 * alpha) + (0.2 * betaMid) - (0.3 * (betaHigh + theta))
betaScore	(0.6 * betaMid) + (0.8 * betaHigh) - (0.3 * (alpha + theta + delta))
gammaScore	(0.7 * gamma) + (0.5 * betaHigh) - (0.5 * (alpha + theta))

Soundscape Design and Audio Engines

The soundscape is composed of five distinct sound sections. These sections work together to create an evolving sonic environment that mirrors the user's cognitive state:

- **SubTone (Delta)**: Low-frequency subtones that represent deep rest or unconscious processing.

- **Harmonics / Musical Fifth Section (Theta)**: A section based on the musical fifth interval, creating layers of overtones that evoke relaxation or meditation.

- **Harmony / Chords Section (Alpha)**: Chordal structures and harmonic progressions based on the central frequency, representing a calm, creative state.

- **Rhythmic Section (Alpha/Beta)**: Rhythmic elements that grow more complex as the user's mental state transitions towards Beta, linked to active thinking.

- **Melody / Arpeggiator Section (Beta)**: A melodic section with arpeggiated patterns that evolve in complexity and speed as Beta waves increase.

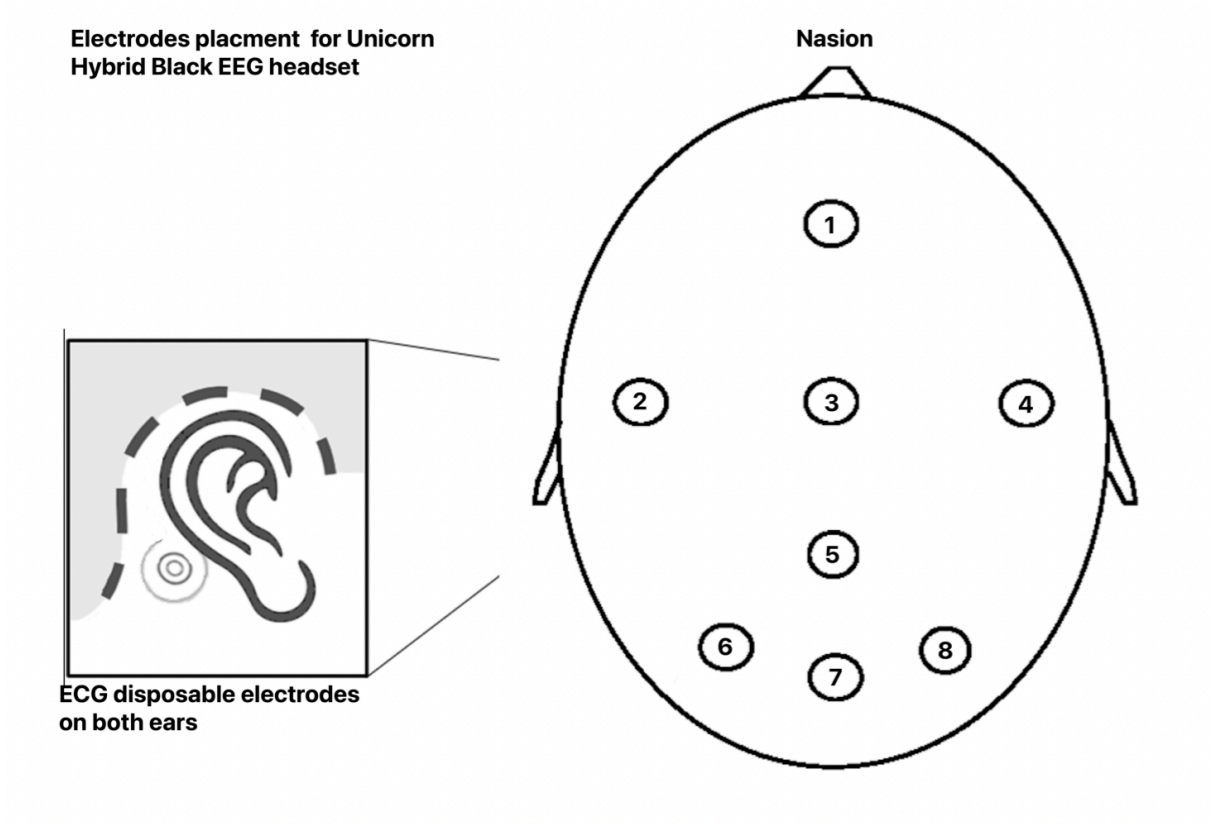
The highest frequency range, Gamma, is handled differently. As the brain moves into this state, the five sound sections are distorted with increased BPM, dissonant harmonics, and random processes, creating a chaotic, intense musical atmosphere that reflects high cognitive load or stress.

Hardware and Software Components – Libraries and Frameworks

The project relies primarily on the EEG headset hardware component. A Unicorn Hybrid Black EEG headset by G.Tec Medical Engineering (See image 2) is used to collect real-time EEG data from participants. This device provides high-quality EEG readings at a sampling rate of 250 Hz with 24-bit resolution. To establish a reference and ground for the EEG headset, disposable ECG electrodes are applied to the mastoid bones behind each participant's ears (See image 3).

Unicorn Hybrid Black EEG headset (Image 2)

EEG cap electrodes placement (Image 3)



The Unicorn EEG headset is accompanied by dedicated software, the Unicorn Suite, which offers various tools and games for recording, visualising, storing data, and conducting real-time brain activity analysis. For this project, the Unicorn Bandpower Add-on is utilised, enabling simple yet efficient UDP connection and data streaming. The Unicorn Suite software requires a Windows machine to operate, as it has not yet been made available for macOS systems.

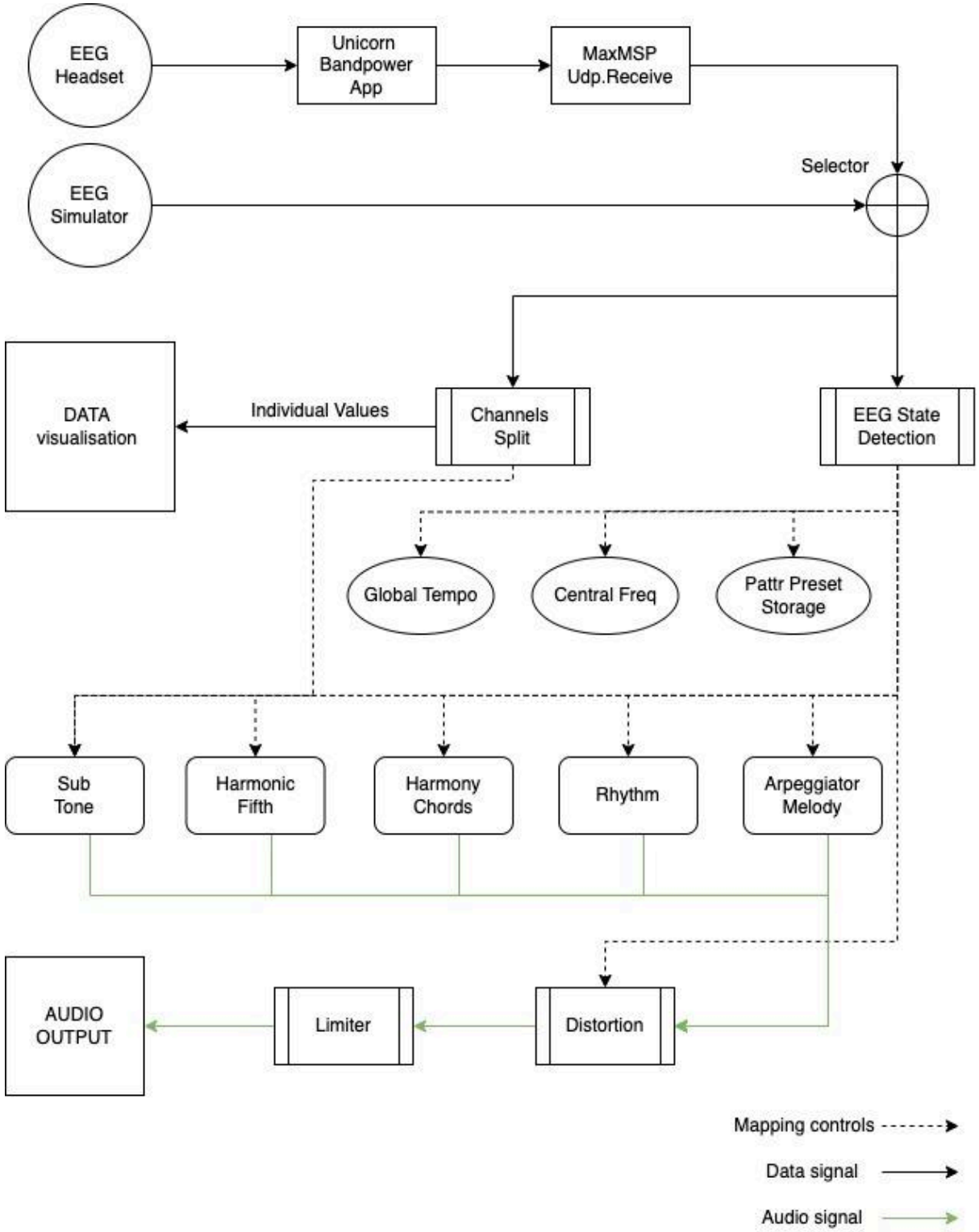
The sound generation is entirely developed in Max 8, which runs on newer versions of the software. To enable the use of Java-based objects, such as *mxj net.udp.recv*—which facilitates the streaming of raw UDP data between the two software programs—Java 8 must be installed.

The FluidCorpusManipulation library by FluCoMa is used in the arpeggiator section to randomise and interpolate between different voices of the synthesiser. The FluCoMa neural network is used to predict points at different states of an x and y table whose position is controlled by frequency bandpowers from the EEG reading.

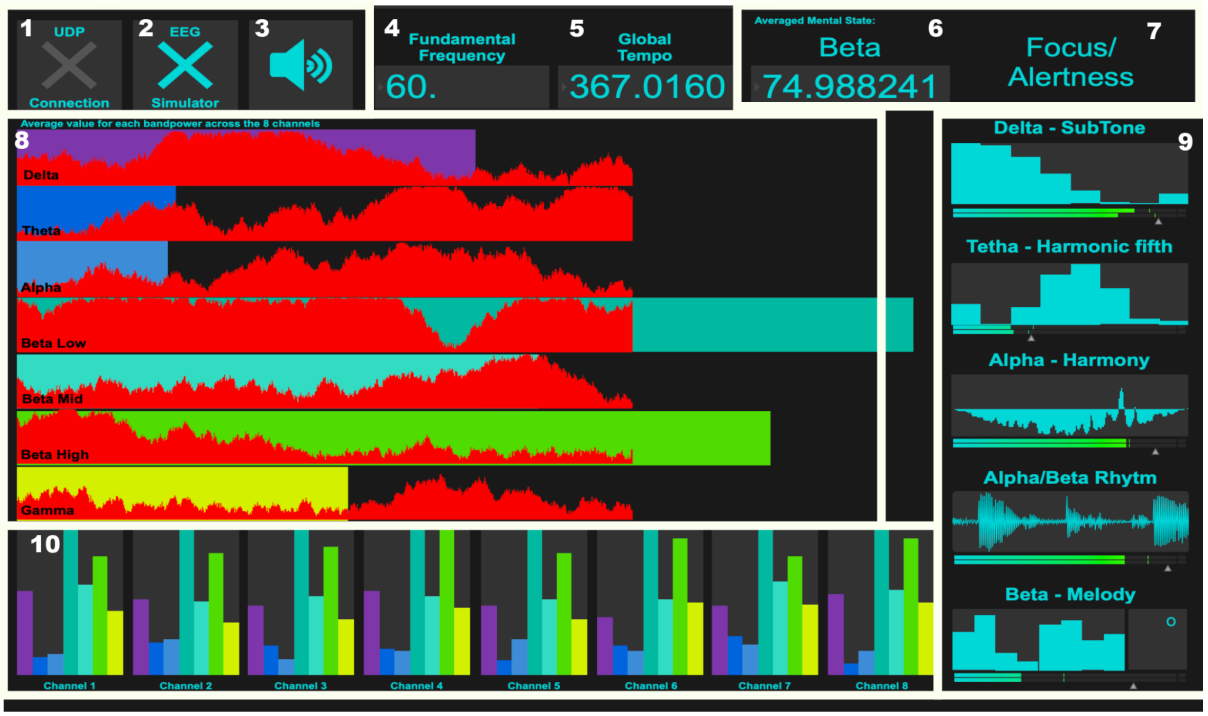
Signal Flow Chart – Code Structure

The entire system can be thought of as a four-stage pipeline: Input Section, Visualisation processing & Mapping, Audio Generation & Output. Raw or simulated EEG band-power data is passed through a selector that lets you switch between live and demo signals. The chosen signal is split into its constituent channels for real-time visualisation, while simultaneously feeding the EEG state detector. The EEG state controls three high-level parameters—central frequency (for tuning oscillators), global tempo (for clocking rhythmic components), and a preset unit (for controlling volumes). These parameters, combined with mappings from the individual channels and mental state, affect five parallel audio engines (SubTone, HarmonicFifth, HarmonyChords, Rhythm, and ArpeggiatorMelody), whose outputs are summed, sent through a fold distortion and limiter, and finally delivered to the audio output.

Signal Flow Chart (Image 4)



Graphical User Interface - GUI (Image 5)

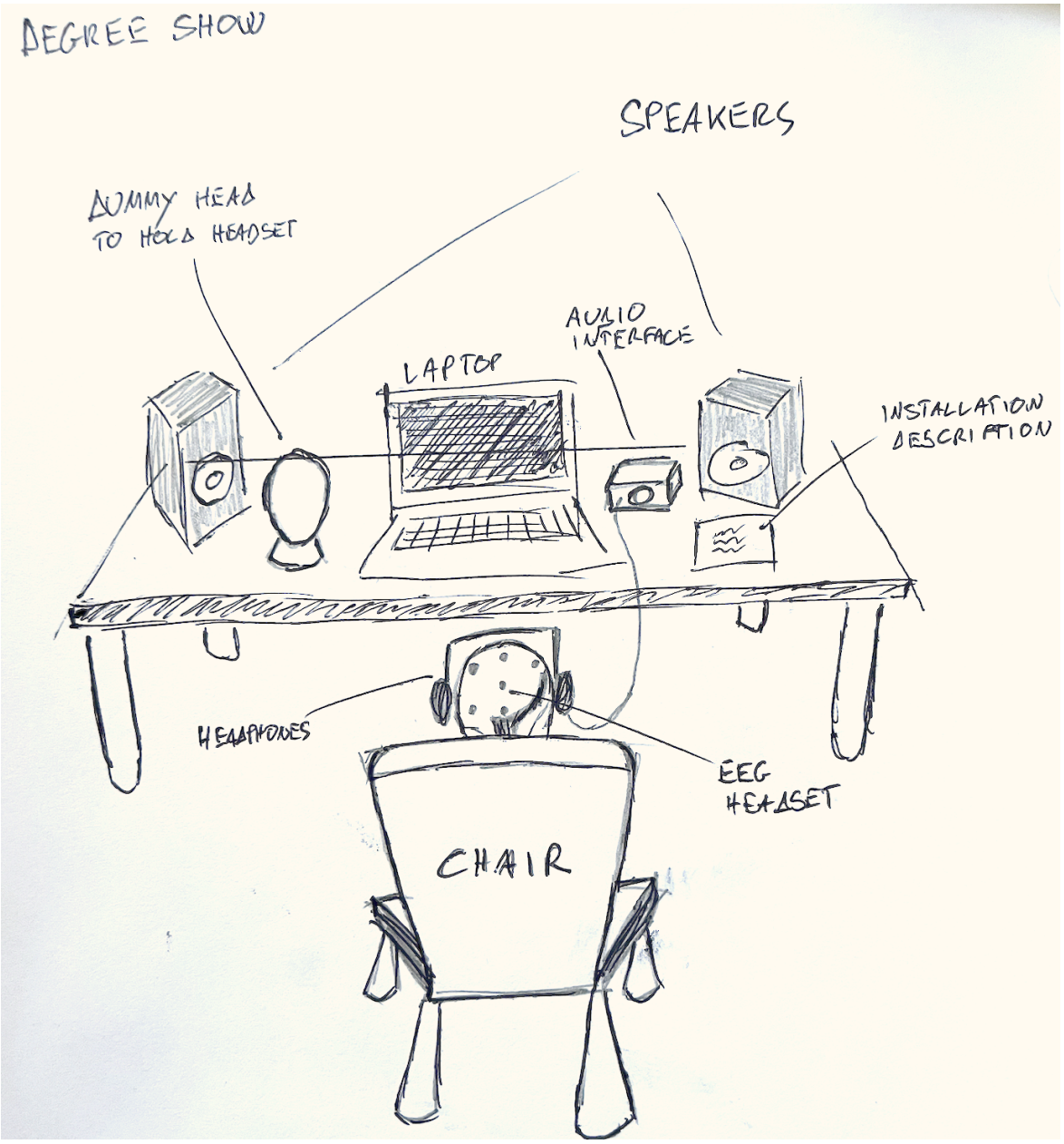


1 - UDP connection On/Off
2 - EEG simulator On/Off
3 - Audio Engine On/Off
4 - Central Frequency (Hz)
5 - Global Tempo (ms - 1/4 mesure)
6 - Detected Mental State and signal ramp
7 - Mental State description
8 - Averaged bandpowers value visualisation
9 - Audio section visualisation
10 - Individual channels visualisation

Degree Show – Immersive Audio Installation

The final installation took place at the Creative Computing, Games Programming, and EMCT degree show 2025. At the centre was a participant's chair positioned in front of a table equipped with a laptop, audio interface, and stereo speakers. The participant wears the EEG headset and headphones to fully experience the immersive soundscapes. A dummy head on the table holds the EEG headset when not in use, while a brief description placed nearby helps visitors understand the experience (See image 5)

First sketch of the show installation (Image 5)



The full implementation of the project is available on GitHub: https://github.com/glanus97/EMCTfinalProject_Sonification-of-Brain-Activity-from-EEG.git.

15. Creative Process

Creative Sound Design – Techniques and Mappings

Once the connection between the headset and Max MSP was established, the main creative challenge became designing the five distinct sound moods. The overall concept was to represent various mental states through sound, beginning with a relaxing, sub-tone ambience for deep relaxation and progressing to frenetic, distorted, and complex music as mental overload occurs. To maintain musical coherence across these moods, all harmonic and melodic components are structured around a central frequency. The initial frequency of 60 Hz was chosen deliberately, as it serves as the foundation for deriving a musical scale that can be used either as the major scale or its relative minor. Every time the central frequency changes, the musical scale is recalculated, with chords generated automatically using the notes within that scale. These chords are used in the harmony/pad section, while the same scale forms the basis for the melody arpeggiator.

As the mental state transitions towards overload, the central frequency gradually increases, and the overall tempo accelerates, creating a sense of overthinking and hyperactivity. To ensure smooth transitions between mental states, timed ramps are employed, guiding the sound smoothly towards the new state whenever it is triggered. Each ramp is set to last 4000 ms, which was a creative choice to balance responsiveness with gradual change. This duration could be changed for different effects and results.

1. Delta State – Deep sleep and unconscious processing

The concept for this state was to create a subtle, relaxing ambience that reflects the calmness of a sleeping state. To achieve this, I chose to use simple sinusoids at very low frequencies. To introduce a sense of movement, eight different sinusoids are slightly deviated from one another, utilising the *increment* message for a multichannel *cycle* object. This approach creates partial frequency cancellation, resulting in an evolving, atmospheric sound.

As the state ramp moves, the increment between each of the eight voices increases, causing the sound to evolve. As the user's brain activity rises, the output frequency gradually transitions from a calm, slow-pace tone to a faster, high-pitched resonance. The amplitude of each voice follows a similar principle, controlled by a multichannel signal with gradual increments across the eight voices. As the mental state intensifies, the speed of the amplitude increments accelerates, adding a dynamic layer to the sound. The only sound section employed in this state is the SubTone, maintaining the serene and ambient quality of the experience.

2. Theta State – Relaxation and meditation

The Theta state is designed to maintain a relaxing and calm ambience while introducing harmonics that evoke a sense of depth. To achieve this, the Delta-SubTone is integrated with harmonic tones layered on top of the central frequency. To reflect a meditative and serene state, I chose to incorporate the musical perfect fifth interval (3:2 frequency ratio), known for its strong consonance and harmonious effect. This interval also appears early in the Fibonacci sequence, linking it to natural harmonic proportions associated with balance and nature (Livio, 2002, p. 2). Research shows that such consonant intervals are processed more smoothly by the brain (Koelsch, 2014, p. 171), supporting emotional relaxation and balance, making it an ideal representation of the Theta state.

Eight different sinusoids are generated, each with an increment rate of 1.5, resulting in intervals of a fifth. The amplitude of each voice is controlled in the same way as in the previous state, using incremented signals to introduce subtle movement between the voices. Each voice is also panned individually, moving according to the signal to create a surrounding, evolving ambience. As the averaged mental state shifts to higher frequencies, the harmonic intervals evolve into dissonant ratios, and the tempo increases. This transition mirrors the progression toward overload and anxiety, enhancing the immersive nature of the experience.

3. Alpha State – Drowsiness and creativity

At this stage, a soft pad sound is introduced to add musical harmony to the output. Using chords derived from the major scale of the central frequency, Markov chains (utilising the *prob* object) are employed to determine the next chord in the sequence. This approach aligns with the concept of gradually increasing cognitive load, with the number of possible chords initially being limited. For example, in the Alpha state, only the 1st, 3rd, 4th, and 5th chords of the scale are triggered. Whereas in the highest state, any chord could be triggered randomly.

This structure mirrors the concept of traditional Western harmony, where different chords of a scale hold different degrees of relevance depending on the fundamental frequency. For instance, the 1st and 5th degrees of a scale have a major significance on the overall musical sequence. As brain activity increases and the tempo accelerates, more chords are introduced into the sequence. As Stephan Koelsch highlights in *Brain & Music* (2012), moving away from the tonal centre to unstable chords is perceived as tensioning, while returning to the tonal centre is perceived as relaxing. Likewise, a tone (or chord) that is harmonically unrelated to a musical tone can produce tension (pp. 31-35). To further enhance this tension, moving to the Gamma state, probability gradually gives way to complete randomness, creating a chaotic and dissonant output that mirrors the escalating mental overload and anxiety.

Chord sequence probabilities (Table 3)

Mental state	Major scale chords (grade/probability)	Switch to relative minor (prob)
Delta - δ	1st/100	0
Theta - θ	1st/60 - 5th/40	0
Alpha - α	1st/35 - 3rd/10 - 4th/20 - 5th/35	30
Beta - β	1st/20 - 2nd/10 - 3rd/20 - 4th/15 - 5th/20 - 6th/15	50
Gamma - γ	1st - 2nd - 3rd - 4th - 5th - 5th minor - 6th - 7th / Random	/

This audio section utilises a polyphonic wavetable synthesiser, where the table offset and zoom are controlled by the Alpha average value and adjusted accordingly to the

mental state ramp. This setup creates an evolving pad sound that dynamically follows the user’s brain activity. Additionally, reverb and equalisation are applied, with their parameters mapped to the EEG data, further enhancing the responsiveness of the sound to the user's mental state.

4. Beta State – Active thinking and concentration

Percussive elements are introduced early in the Alpha state, becoming progressively more intense as the mental state advances to higher levels. A drum machine based on Euclidean rhythms forms the rhythmic backbone of this section. At regular intervals, the Euclidean pattern is re-triggered to generate different random patterns, allowing the rhythm to mutate over time. The intention was to gradually introduce percussive elements, following with the increasing tempo. In the Alpha state, a kick sound is introduced, and as the state progresses toward Gamma, additional percussive sounds are layered on top of the initial kick. By the final state, a total of eight different percussive samples are triggered. As the tempo accelerates and more elements are added, the goal was to create a sense of randomness and chaotic rhythms. The drum samples used in this section are compressed and equalised to ensure a cohesive sound.

Alongside the rhythmic components, a melodic element is gradually introduced at this stage. A simple random arpeggiator is employed to create lead melodies in tune with the central frequency scale. The arpeggiator randomly switches between ¼, ⅛, and 1/16 note durations. Initially, the melody alternates between on and off, providing a decorative layer to the overall soundscape. As the system progresses towards the Gamma state, the arpeggiator becomes more active, eventually remaining consistently on, contributing to a hyperactive and overloaded output.

In this state, the objective was to create a complex soundscape that still adhered to logical and musical processes. The harmonic, melodic, and bass elements are all in tune with one another, and the rhythmic engine is designed to generate engaging and enjoyable patterns of percussive elements, despite the randomic nature of the sound.

5. Gamma State – Stress or high cognitive load

As the brain activity reaches its highest state, the musicality and enjoyability of the soundscape are gradually eroded through the use of distortion, chaotic rhythms, and dissonances. The SubTone and its harmonics are increasingly deviated from each other, producing high-pitched noise. The central frequency steadily rises, reaching 70 Hz, while the global tempo accelerates to approximately 180 BPM. The individual notes of each chord are randomly deviated from one another, resulting in dissonant harmonies, and the sequence becomes entirely unpredictable. The arpeggiator now plays continuously without pauses, generating random sequences, while all percussive elements are equally present in the mix.

To enhance the sense of overload, a fold distortion is applied to the sum of all audio signals, except the sub-bass. The intensity of this distortion increases in response to the mental state, reflecting a hyperactive and anxious mental condition. This cumulative effect creates a chaotic and overwhelming soundscape, mirroring the heightened mental state of the user.

GUI – Graphical User Interface

The GUI is primarily designed to visualise the incoming data from the EEG headset and display the current mental state, along with its relative meaning, while offering minimal control options. These controls allow the user to activate or deactivate the simulator, manage the UDP connection, and activate the audio engine. The raw EEG data is visualised for each of the eight individual channels, as well as the average values for each frequency band across those channels.

Each frequency band is associated with a specific colour to visually reflect its meaning. Lower frequency bands, such as Theta, Delta, and Alpha, are represented with cooler tones (purple and blue), while higher frequencies are depicted with brighter colours (light blue, green, and yellow). The GUI also includes simple visual indicators to show the activity of each of the five sound engines. The amplitudes of the SubTone, arpeggiator, and harmonic fifth voices are visualised using multisliders. The wavetable state for the pad is displayed, and an amplitude scope is used for the

rhythmic section. Each component has its own gain display, allowing users to see which element is actively contributing to the sound at any given moment.

Iterative Design and Creative Process

The development of the soundscape was guided by an iterative design process rooted in personal exploration. Without direct user feedback during creation, I relied on trial and error—adjusting variables such as frequency ranges, layering techniques, and responsiveness to movement and mental states—based on my own emotional reactions and sense of immersion. Each iteration brought the experience closer to a state where the sounds felt meaningfully connected to internal changes, with improvements made to pacing, complexity, and dynamic range. I often tested how shifts in breathing, thought patterns, or physical motion would affect the output, using those reactions as a starting point. Although the design process was entirely self-directed, the final user survey offered valuable retrospective validation. Many participants described feeling immersed and emotionally engaged, with several noting that the soundscape responded intuitively to their mood or movement. Comments like “the sound matched my energy” and “when I relaxed, it slowed” (Sonification of brain Activity Feedback, May 2025) confirmed that the iterative refinements made during development successfully created a system that felt responsive, alive, and personally meaningful to its audience.

16. Debugging and problem solving

Choice of Hardware and Setup

The first step in realising this project was to determine the direction to take regarding the hardware components, particularly the EEG device. Initially, I considered using a commercial device such as the Muse 2 or Flow tDCS. These products are more affordable, but they offer lower accuracy and flexibility of the recorded data. Through my supervisor, Dr. Atau Tanaka, I was able to access the Unicorn headset, which, while still a commercial device, provides significantly superior data quality.

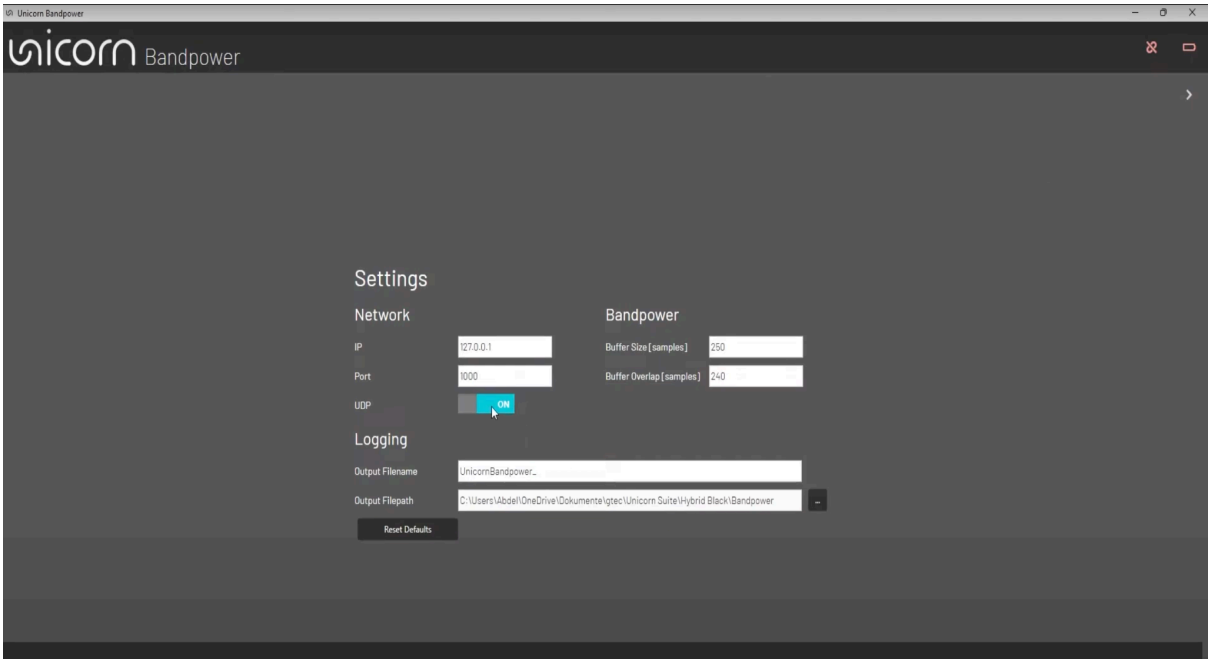
Once the EEG headset was secured, another issue emerged. The Unicorn Suite software is only compatible with Windows systems, which meant I had to either use a Windows emulator on my Mac or run the project on a Windows machine. I opted for the latter approach, as it simplified the process and facilitated more seamless communication between the Unicorn Software and MaxMSP.

Installation – Software and UDP Communication

Working on a Windows machine allowed for a smooth installation of the Unicorn Suite software. As previously mentioned, the Unicorn Suite offers a range of tools to read, record, and process EEG data. The Bandpower Add-on was chosen primarily for its simplicity and the efficiency of its UDP communication functionality. From the app settings, the serial port and IP address can be configured, UDP communication can be activated, and the buffer size can be adjusted (See image 6). Each time I switched laptops or relocated, the IP address had to be updated to ensure proper communication.

During the development phases, when I was using two different machines to run the Unicorn Software and MaxMSP, I needed to ensure that the UDP communication was set to the receiver laptop's IP address. It is important to note that any changes to the settings require restarting the Unicorn Suite to ensure the proper synchronisation of the software.

Bandpower App settings (Image 6)



To stream the data correctly into MaxMSP, I initially attempted to use the *udpreceive* object, which is part of the CNMAT OSC library and supports simple OSC data streaming. However, a problem arose because the *udpreceive* object expects data in OSC format (4-byte) and was reporting errors each time data was received. The Unicorn software, on the other hand, sends raw UDP data in the form of float values. To properly handle this data, I had to switch to a Java-based object, *mxj net.udp.recv*, which is capable of reading raw UDP data. This allowed for correct parsing and processing of the incoming data stream from the Unicorn software.

Data processing and weighted averaging

With the raw UDP data successfully streaming into MaxMSP, the next challenge was to extract usable values for audio processing. The incoming signal was formatted as lists of 70 float values separated by commas. To eliminate the commas, the *fromsymbol* object was used to strip the comma symbols, and then the *zl.group* object was applied to reassemble the values into lists of size 70. These lists were then processed using two separate JavaScripts: one to separate and regroup the eight different electrode channels, and another to extract the individual averaged bandpower values (indices 57 to 63).

Starting with the individual averaged values, the goal was to replicate the mental state detection system used in the Bandpower app. Initially, I attempted to simply compare the amplitude values to identify which one had the highest value. However, this approach led to consistently detecting the Delta/Theta state, as these frequency bands typically yield stronger readings, which did not accurately reflect the user's mental state. As a result, I implemented a more nuanced approach using another JavaScript, where the frequency scores were derived from the factorised sum of adjacent frequency ranges, with the subtraction of opposing values.

Through a process of trial and error, I managed to obtain results that closely aligned with the Bandpower app's readings. While this system worked reasonably well, I found that it was too stable and did not respond sufficiently to movement or shifts in brainwave activity. To address this, I adjusted the factorising values to make the system more responsive. Though this adjustment reduced the accuracy of the mental state detection, it was a conscious decision. For the creative goals of this project, I prioritised creating an audio-reactive system that users could influence through their actions, choosing responsiveness over precise accuracy to enhance the interactive experience.

Filtering of Data, CPU Limitations and Adaptability Issues

Another challenge that emerged during the musical development of the project was that each time a new list of EEG values was received, the EEGstate patch would output the state detection. The mental state is output as a symbol message, and a selector is used to trigger a 4000-ms line ramp that moves towards the corresponding value. However, these ramps were triggered for each new list at a rate of 25 samples per second. This caused a problem where the destination value could never be reached, as new four-second ramps were continuously retriggered with every new sample. To resolve this issue, I inserted a *change* object into the data pipeline before the line ramp was triggered. This object filters out repeated values, ensuring that the line ramp is only triggered when the mental state changes. This adjustment allowed the system to reach the intended destination value, preventing

the continuous retriggering of ramps and enabling a smoother transition between mental states.

As the project grew in size and complexity, a significant issue arose: the audio engines and the numerous mappings throughout the project placed a heavy strain on the CPU usage. Working with an i7 generation CPU, I found that I had to limit the number of audio engines and the associated EEG data mappings to prevent the system from overloading. Ideally, I wanted to establish more one-to-one mappings between EEG data and sound effects such as distortions, reverbs, or delays, allowing for a more noticeable reactivity to actions like blinking or clenching teeth. For instance, the individual values from the frontal channels could have been linked to a global reverb effect, so that eye movements would cause the reverb to increase. However, to achieve this level of interactivity, I would have needed either more powerful hardware components or a shift to a more efficient programming language than MaxMSP. Unfortunately, neither of these options was feasible at the point when I encountered this challenge. As a result, I had to prioritise minimising CPU overload by simplifying the system. This meant reducing the complexity of the mappings and limiting the number of audio engines, which ultimately restricted the depth of interactivity I had initially envisioned for the project.

During the final presentation of the project at the degree show, I encountered some minor issues related to the adaptability of the experience for a wide range of visitors, which impacted the accuracy of the EEG readings. To effectively capture EEG data, the headset needs to be tightly secured on the user's head, as the electrodes should make direct contact with the scalp to provide accurate readings. Since participants of different ages and genders were using the same EEG cap—changing the size each time was not possible—this caused variability in the signal quality. The amount of hair also plays a role in affecting the signal (Koelsch, 2012, p. 43), and for some participants, it was nearly impossible to ensure that the electrodes were making proper contact with the skin.

Additionally, conductive gel is typically suggested to be applied to the electrode ends to optimise their performance. However, applying the gel would have introduced significant logistical challenges, especially with a high volume of visitors wanting to

try the experience. Despite these minor setbacks, they did not hinder the overall participant experience, as the precise accuracy of the EEG data was not critical for the objectives of the installation. The installation's primary focus was on the interactive and immersive nature of the soundscapes, which participants were still able to engage with, even if the EEG readings were not perfectly accurate.

17. Self-evaluation and Conclusions

Success of the Project Based on Initial Goals

The project was largely successful in achieving its central goal, which was to create an immersive experience where sound reflects the user's mental state in real-time through EEG data. Many participants reported feeling that the soundscapes were responsive to their emotional and cognitive states. Feedback from the users confirmed that the project met its objective of generating music that evolved based on brainwave signals, aligning with the emotional and mental conditions of the participant. This aspect of the project — the direct translation of EEG signals into generative sound — was realised effectively, providing both artistic and scientific insight into the potential of neurofeedback-driven music.

Evolution of Goals and Project Scope

Initially, I aimed to create a laptop-free experience for the user, utilising devices like Bela or Raspberry Pi to run the sound engine independently. However, after further reflection and based on user feedback, I realised the value of displaying real-time EEG data. This decision was instrumental in ensuring that users had a clear understanding of how their brain activity influenced the sound. The presence of the screen provided valuable insights and allowed participants to visually track the evolution of their mental states throughout the experience, helping them understand how to control their brain activity.

To better explore the retroactive influence of sound on the brain, I should have divided the experience into two parts: one where users could experience how their brain activity influenced the sound, and another where different moods could be played while recording the EEG data to examine reactions. In retrospect, this division could have helped, though the current single-session structure still yielded valuable data. Despite the adjustments I made, I believe the project was appropriately scoped.

Testing and Appropriateness of the Approach

The testing phase was crucial to evaluating the project's effectiveness. I engaged multiple participants who had the opportunity to try the headset and experience the sound installation. This testing was instrumental in understanding how well the system reflected the users' brain activity and how the sound evolved based on their mental and emotional states. Feedback was collected through a survey that asked participants to reflect on their experience, which provided valuable insights for future improvements (Sonification of brain Activity Feedback, May 2025, accessible via GitHub Repository)(Lanus, 2025).

The testing process was mostly appropriate because it directly aligned with the core goal of the project: to assess how EEG data could be used to generate responsive sound that mirrors the mental states of the users. However, as mentioned above the testing process should have been structured differently to propery address the second research question, regarding the potential music-brain feedback loops. The user’s feedback also emphasised the importance of user engagement and how the real-time display of brainwave data contributed to their understanding of the experience. The comments confirmed the overall success of the project but also pointed out areas that could be refined, particularly regarding user control and the clarity of the EEG-to-sound relation.

Creative Process – Successes and Areas for Improvement

Several aspects of the creative process worked well. One of the most significant achievements was the engagement and reactivity of the sound system. Most participants felt that their actions and mental states were mirrored in the sound, confirming the validity of the EEG-to-sound mapping. However, not all users were able to fully control the sound, which was an important realisation. The difficulty in controlling brain activity highlighted the challenge of fine-tuning the system for different users. Some users needed more time to understand how to modulate their brain activity to influence the sound, while others struggled to engage with the system at all (Sonification of brain Activity Feedback, May 2025).

The project also benefited from its individual and personal nature, as many users were drawn to the experience of scanning their own brain activity and hearing the sound reflect their own mental state. The idea of having a personalised connection with the sound through EEG data was particularly appealing to visitors. However, the user interface (UI) proved to be a point of confusion for some participants. The amount of information displayed on the screen could be overwhelming, and simplifying the UI would likely enhance the experience. Additionally, although the sound mappings were effective, they were limited by CPU constraints. With more computational power, I would be able to expand the mappings to include immediate spikes in brain activity caused by actions such as clenching teeth or blinking eyes, making the experience more dynamic and responsive to user movements.

The environmental setup also impacted the project. The experience would have been more effective in a controlled environment with fewer distractions and background noise. The presence of multiple listeners during the experience might have made some participants self-conscious, which could have interfered with their mental states and thus affected the EEG readings. A more intimate and focused setting would likely result in more accurate and meaningful data.

Problem Solving and Future Directions

The approach to problem-solving in this project was generally successful. While there were challenges, such as managing CPU overload and balancing the complexity of sound design with technical limitations, these were resolved through thoughtful adjustments. The project's success lies in its ability to provide a functional and interactive experience within the scope of the resources available. Moving forward, expanding the project using different coding languages or platforms, such as more reliable sound engines, could improve computational efficiency and open up further creative possibilities.

Looking to the future, there are several ways the project could be developed. First, expanding the range of sound output would add complexity and depth to the user experience, allowing for a wider variety of emotional responses and more nuanced soundscapes. The reactivity of the system could also be improved by incorporating more immediate audio responses to specific actions or thoughts. The development

of a fully immersive experience is another avenue for future growth. Creating a controlled, quiet environment where users can engage with the installation without distractions would improve the overall impact of the experience. Enhancing the graphical user interface (GUI) with more engaging visuals and making it easier to understand would help participants feel more connected to the system.

Lastly, refining the detection of mental states to make the system more adaptable to individual users would make the experience more personal and responsive. This would involve fine-tuning the weighted comparison process to different users and providing a personalised control for the users, allowing them to shape the system to better reflect their mental state.

Conclusions

In conclusion, this project successfully explored the intersection of brain-computer interfaces and generative music, achieving the goal of creating a soundscape that responds to the user's brain activity. While the project met many of its objectives, the feedback from users provided valuable insights into areas that could be improved.. By incorporating these suggestions and further developing the technical and creative aspects, this project has the potential to evolve into a more immersive and intuitive experience. Through ongoing refinement and future iterations, the project could lead to new understandings of the relationship between sound and the brain, offering applications in areas such as music therapy, cognitive enhancement, and interactive art installations.

Use of generative AI tools

I acknowledge the use of ChatGPT (https://chat.openai.com/) to refine the academic language and accuracy of my own work. On 19th May 2025, I submitted separate sections of my essay with the instructions to “Correct this text to make it clearer and more readable. Try to keep the style and word choice as close as possible to the original”.

The output (Final Project Report) was then modified further to better represent my own tone and style of writing.

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Appendix

- **Code GitHub Repository –** https://github.com/glanus97/EMCTfinalProject_Sonification-of-Brain-Activity-from-EEG.git

- **Audio Output Recordings –** https://github.com/glanus97/EMCTfinalProject_Sonification-of-Brain-Activity-from-EEG/tree/main/AudioOutput_recordings

- **EEG Simulator Video Demo –** https://github.com/glanus97/EMCTfinalProject_Sonification-of-Brain-Activity-from-EEG/tree/main/EEG_Simulator_Video

- **Users' Feedback Survey Transcript –** https://docs.google.com/spreadsheets/d/1apCUmcVgvuxHihOIPgq-B-p24S_YyJ-nUbwNH_XfZdA/edit?usp=sharing