Developing Brain-Computer Music Interfaces for Meditation

Krisztián Hofstädter

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ANGLIA RUSKIN UNIVERSITY

ABSTRACT

FACULTY OF ARTS, HUMANITIES AND SOCIAL SCIENCES

CAMBRIDGE SCHOOL OF CREATIVE INDUSTRIES

DOCTOR OF PHILOSOPHY

DEVELOPING BRAIN-COMPUTER MUSIC INTERFACES FOR MEDITATION

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This practice research developed two prototype brain-computer music interfacing (BCMI) systems to support meditation practices. The second, more advanced system, BCMI-2, was tested to help induce and maintain a specific meditative state, the shamanic state of consciousness (SSC), first with two trainees in a non-clinical neurofeedback training (NFT) setting and then with my own brain signals in an artistic performance setting. In both settings, the system generated soundscapes with two entrainment methods to support the meditation: (1) auditory rhythmic entrainment (ARE) generating drumming gradually decreasing in tempo and rhythmic complexity and (2) a neurofeedback protocol rewarding increased theta brainwaves at Fz with a reward sound embedded as an integral element within the computer-generated drumming. In addition to these techniques, the performance setting also mapped hemispheric coherence measurements to surround sound spatialisation to help increase my and the meditating audience's feeling of immersion. The main contribution of this research is the creation of the BCMI-2 system and recommendations based on the knowledge gained while developing and testing its suitability to support meditation practices in NFT and artistic performance settings. BCMI-2 is fully open-source, affordable and uses the research-grade OpenBCI Cyton electroencephalograph to record multi-channel brain signals. The project contributes practical knowledge to the field. It could be of interest to NFT practitioners wishing to design immersive soundscapes for neurofeedback protocols, artists wishing to express themselves with physiological computing and meditation practitioners wishing to understand meditation from a scientific perspective.

Keywords: altered state of consciousness, artistic performance, brain-computer music interfacing, auditory rhythmic entrainment, electroencephalography, computer-generated music, interactive soundscapes, meditation, neurofeedback training, shamanic journeying, surround sound

Project Updates and Contact Details

Besides my university's repository, the thesis will also be archived on https://phd.khofstadter.com. This website will include a copy of the work with embedded audio and video players, and an erratum if needed. The website will also provide updates on the project as well as my up-to-date contact details.

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Acronyms and Definitions

- ASC: Altered state of consciousness. Out of the five types of ASCs outlined by Vaitl et al. (2005), namely (1) spontaneously occurring (e.g. during sleep, dreaming or near-death experiences); (2) physically or physiologically induced (e.g. by starvation, diet or sexual activity); (3) psychologically induced (e.g. by sensory deprivation, hypnosis, biofeedback, meditation or rhythm-induced trance); (4) disease-induced, (e.g. in psychotic disorders or epilepsy) and (5) pharmacologically induced (e.g. with psychedelic drugs), this thesis focused on psychologically induced ASCs through meditation, neurofeedback training and rhythmic auditory entrainment.
- BCMI: Brain-computer music interfacing.
  - BCMI-1: the BCMI system developed in the BCMI-1 project (Chapter 4).
  - BCMI-2: the BCMI system developed in the BCMI-2 project (Chapter 5) to address the limitations of BCMI-1.
- BPS: Beats per second.
- CNS: Central nervous system.
- EEG: Electroencephalogram.
- NFT: While the terms 'neurofeedback', 'neurofeedback training', 'neurofeedback therapy', 'neuro therapy', 'neuro-biofeedback' and 'brainwave biofeedback' have been used fairly interchangeably in the literature, the most commonly used terms are 'neurofeedback' and 'neurofeedback training'. As 'neurofeedback' technically does not necessarily imply training, in this thesis, I use 'neurofeedback training' (NFT) to refer to the practice in which BCI systems provide feedback on neurological activity to trainees for a specific length and regularity of time that is defined by trainers in clinical or non-clinical settings (Section 3.2).
- ARE: Auditory rhythmic entrainment, a specific type of auditory entrainment that uses rhythm to stimulate and re-pattern neurological functions (Section 3.4).
- meditation: A set of mind-body practices that, by regulating attention, can help induce a variety of physiological and mental changes, from simple relaxation to dramatic mystical experiences (Section 3.3).
- neuromarkers: Also called neural correlates. Specific brain activities that correspond with particular experiences. Some neuromarkers of meditative states are discussed in Sections 3.2, 3.3 and 3.4.

- NOR: Non-ordinary reality (internal experience during shamanic journeying).
- shamanic journeying: A specific type of guided meditation used in shamanic traditions that aims to help practitioners enter an ASC in which they can communicate with 'spirits' in a mental image and retrieve specific information from them (Section 3.4.3).
- SSC: Shamanic state of consciousness. A specific type of ASC that can be induced with shamanic journeying (Section 3.4.3).
- visual imagery/visions: Internal visual imagery experienced with visualisation (e.g. in guided meditation with eyes closed).
- breakthrough: A breakthrough, also called a 'crossover' in meditation, happens when the normal waking state of consciousness shifts into an ASC (Sections 3.2.4 and 3.3.1).

Chapter 1

Introduction

1.1 Overview of the Thesis

The overall design of my research is grounded in practice and demonstrated through a portfolio of creative works and this written commentary. It is a proof-of-concept research study in which I developed a prototype brain-computer music interfacing (BCMI) system to support meditation practices in neurofeedback training (NFT) and artistic performance settings. To help induce and maintain meditative states, the system provides customisable neurofeedback protocols and customisable auditory entrainment. To develop this system, I explored the intersections of various domains, including brain-computer interfacing (BCI), NFT, neurogaming (NG), sound and music, music therapy and meditation (Fig. 1.1).

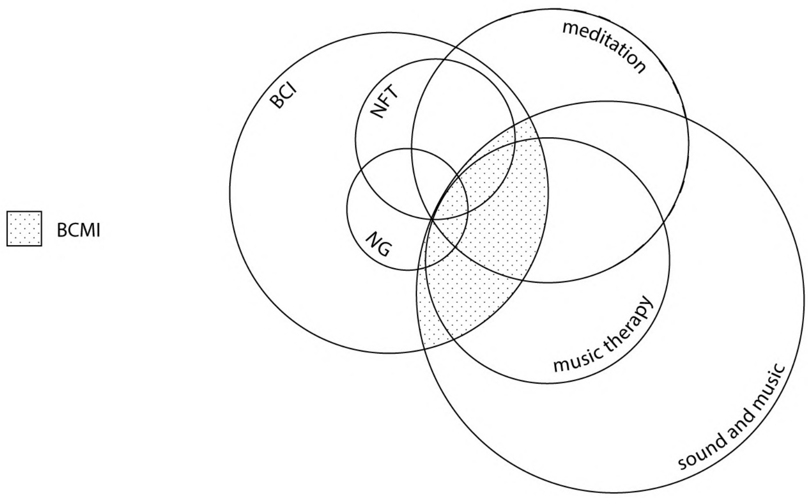

Figure 1.1: Venn diagram of the intersecting research domains.

The thesis comprises a portfolio of creative works and this written commentary, which includes six chapters. The portfolio includes the outcomes of two consecutive projects, each dedicated to developing a BCMI system: the single-channel BCMI-1 system in the first project and, to address its limitations, the multi-channel BCMI-2 system in the second project. BCMI-1 uses a dry sensor with a consumer-grade electroencephalograph to record brain signals, and BCMI-2 uses wet sensors with a research-grade electroencephalograph. **The main contribution of this research is the creation of the BCMI-2 system and recommendations based on the knowledge gained while developing and testing its suitability to support meditation practices in NFT and artistic performance settings.** This chapter introduces the research, Chapter 2 outlines the project management methodology, Chapter 3 reviews the relevant literature and Chapters 4 and 5 reflect on the projects that led to the development of BCMI-1 and BCMI-2. Finally, Chapter 6 concludes the research and outlines future directions.

1.2 Knowledge Gap

The domain of human-computer interaction (HCI) investigates how humans communicate with computers. HCI offers various applications that can map biological signals to feedback. One of these biofeedback applications is NFT, in which BCI systems provide feedback on neurological activity in real time. The most frequently used brain signal in NFT is the electroencephalogram (EEG), which is recorded using electroencephalograph machines. In EEG NFT, neurofeedback protocols provide feedback to users by mapping classified brain signals to visual, auditory or haptic control parameters (Fig. 1.2).

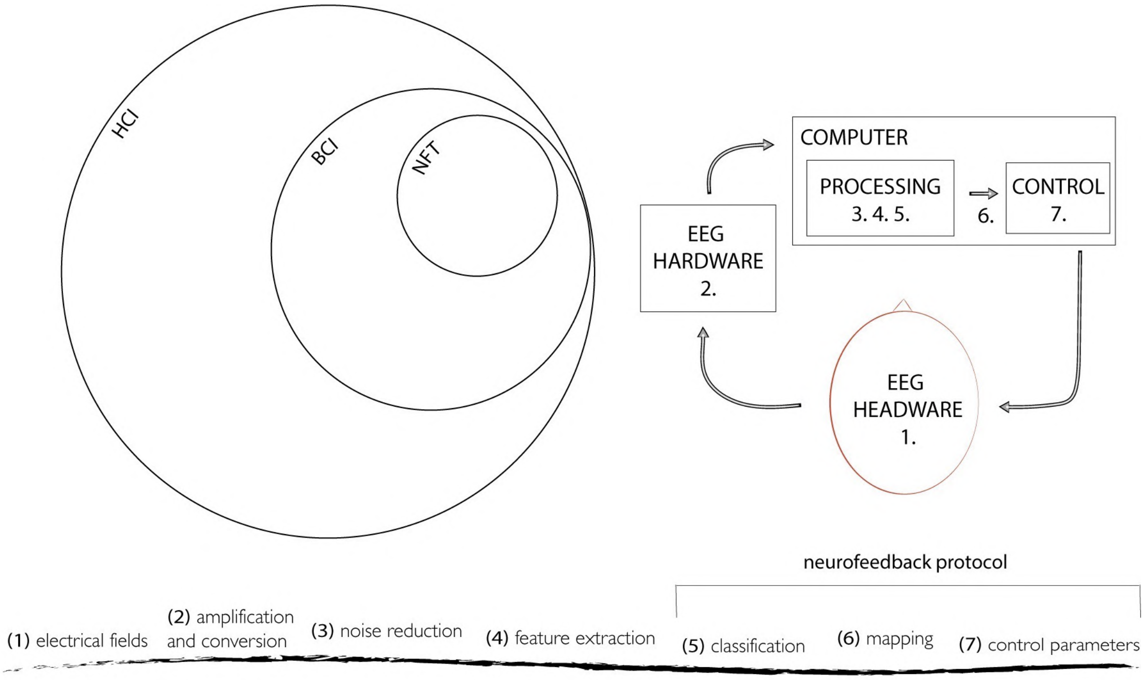

Figure 1.2: Venn diagram (left) depicts BCI as a subdomain of HCI and NFT as a subdomain of BCI. Two drawings (bottom and right) depict the BCI interfacing steps, with the bottom one indicating the steps controlled by the neurofeedback protocol.

Existing NFT systems mainly focus on giving visual feedback (Steffert, 2018, p.136) and where they provide options for auditory feedback, these options are often limited, not allowing the development of engaging musical experiences (i.e. they do not employ the wide-ranging capabilities of music that could help induce and maintain the desired states of mind) (Miller, 2011; Mealla. et al., 2014; Steffert, 2018, p.84). Numerous biofeedback systems have generated engaging music in real time since the 1960s in artistic performance and, more recently, in academic research settings. However, when NFT systems provide auditory feedback, they often simply trigger short sounds or increase the volume of pre-recorded music. While these simple techniques have been shown to be effective (Gruzelier, 2008; Fedotchev, Radchenko and Zemlianaia, 2018; Tarrant, 2020; Fedotchev et al., 2021), my literature review and discussions with relevant researchers encouraged me to enhance these methods, especially for applications that use auditory feedback only (e.g. in eyes-closed alpha-theta training linked to meditation practices). When choosing auditory-only over other feedback modalities (visual, haptic or combined), aligning the aesthetics of this feedback (Collura, 2017, p.184) and the sonic context in which it is embedded with aspects of the entrained affective state should help deepen users' engagement and thus benefit the BCI learning process. Furthermore, the benefits of enhancing user engagement in systems using passive (unconscious) BCI control should also be considered, as the more immersed users are in an experience, the more likely they can let go of active (conscious) control.

A much older technique than NFT that has also been used to alter the state of mind is meditation, which is often practised with eyes closed. It is a set of mind-body practices that, by regulating attention actively or passively, can help induce various physiological changes that range from simple relaxation to dramatic mystical experiences in altered states of consciousness (ASCs). Attention regulation is more active in concentrative and more passive in receptive types of meditation (Washburn, 1978). All neurofeedback protocols aim to develop brain control, with some specifically supporting meditation practices (e.g. in NeuroMeditation (Tarrant, 2020)). The protocols in this last category combine the ancient wisdom of meditation with modern computer science by providing immediate feedback on internal states.

Another ancient technique, in which the pulse of repetitive stimuli is used to alter the state of mind, is auditory entrainment. This technique has been used with drumming in a specific type of guided meditation called shamanic journeying to help induce and maintain an ASC called the shamanic state of consciousness (SSC) (Flor-Henry, Shapiro and Sombrun, 2017). Depending on the specific tradition, the tempo and rhythmic complexity of the drumming in shamanic journeying sometimes change (Wilcken, 1992; Strong, 1998; Maas and Strubelt, 2003) and sometimes remain consistent (Harner, 2013; Hove et al., 2015). Based on my literature review, discussions with shamanic practitioners and my own experience of drumming while meditating, I decided to implement auditory rhythmic entrainment (ARE) with gradually decreasing tempo and decreasing rhythmic complexity in my BCMI-2 system. I then tested the system's suitability to support meditation in NFT and artistic performance settings.[1]

[1] In a book chapter titled 'Journeys Around the Secret Place' (Hofstädter, 2022), I discuss my 20-years-long research exploring psychologically induced ASCs (Vaitl et al., 2005) through various meditation, artistic and scientific practices. After marking the initial ASC experience that started my investigation, the chapter outlines my first experiments with poetry, painting, meditation and electronic music, which I used to help express and revisit this initial experience. Then, the chapter outlines the three projects that developed BCMI systems (BCMI-0, BCMI-1, BCMI-2) and discusses how the last one employed a neurofeedback protocol and ARE to help induce and maintain an SSC. In light of the recent renaissance in the study of psychedelic substances in academia (Carhart-Harris et al., 2021) and an increased interest in the subject in the business world (Rebel Wisdom, 2022), this chapter emphasises that not all shamanic traditions have used psychedelics to access hypnagogic states, and, therefore, meditation and perhaps ARE should be considered as more secure alternatives or complementary methods.

1.3 Contribution to Knowledge

BCMI-2 is a stable system that combines two entrainment methods (neurofeedback protocols and ARE) in a novel way in order to support meditation practices. It embeds the neurofeedback reward sound as an integral element within the ARE, creating interactive and engaging soundscapes. BCMI-2 uses an affordable, research-grade OpenBCI board to measure, digitalise and amplify multi-channel EEG in combination with the free audio programming environment SuperCollider for the remaining interfacing steps. BCMI-2 is fully open-source and, from the acquisition step onwards, customisable within one programming environment, the SuperCollider Integrated Development Environment (IDE). Removing the need to run multiple software applications or IDEs simultaneously (e.g. one to process EEG and another to generate music) improves clarity. Finally, for those interested in developing new BCMI systems based on BCMI-2, SuperCollider offers high-quality audio and versatile composition tools and a vibrant research community available for help if needed.

Users with basic programming skills can customise BCMI-2's neurofeedback protocols and ARE parameters effortlessly. We can select up to eight channels to record raw EEG signals and extract multiple frequency bands and phase coherence features from these signals. We can classify these features and then map them to sound control parameters for NFT or other, more artistic, sonification purposes. Furthermore, we can adjust the tempo and rhythmic variability of the ARE generator and replace the default frame drum samples with different ones. Additionally, BCMI-2 can spatialise sound in stereo or 4.0 surround. Although this research only tested the system to induce and maintain the SSC, by adjusting these parameters, we can entrain other meditative states (e.g. related to strong alpha brainwaves or hemispheric coherence). This is important, as end-user personalisation has been demonstrated to play an important role in the effectiveness of EEG NFT (Mealla. et al., 2014) and because it provides a variety of creative options for artistic performances. I plan to develop BCMI-2 further and to invite researchers with advanced programming skills to contribute new feature extraction methods and sound control parameters via the projects' GitHub repositories.[2]

To test BCMI-2's suitability for supporting meditation, I customised its neurofeedback protocols and ARE parameters to help induce and maintain the SSC. I trialled this combination first in an NFT setting (Section 5.4) with two participants, and then – as a natural progression – in an artistic performance setting (Section 5.5). In both settings, I customised the neurofeedback protocol and the ARE parameters to help entrain the theta brainwaves associated with ASCs (Strong, 1998; Gruzelier, 2008; Jovanov and Maxfield, 2011; Collura, 2017, p.134).

I set up BCMI-2 with the following:

[2] The BCMI-2 software parts can be found at https://github.com/khofstadter/OpenBCI-SuperCollider and https://github.com/khofstadter/bcmi-sc01-shamanic-soundscape-generator. I discuss these parts in Chapter 5.

- a custom ARE generating drumming that is gradually decreasing in tempo and rhythmic complexity
- a neurofeedback protocol that plays shaker sounds to reward strong theta brainwaves

In the performance setting, besides creating interactive music with the above two methods, I also improvised on an acoustic frame drum, the sounds of which were transformed with effects and then spatialised with brain coherence features extracted with BCMI-2. The coherence to spatialisation mapping was not part of the neurofeedback protocol. I did not use it for operant conditioning. Instead, it was an abstract interpretation, an artistic sonification, with which I aimed to help myself and the audience become more profoundly immersed in the experience. These acoustic and transformed sounds aimed to interpret my internal meditation process. After this performance, I conducted an online listening study without the interactive audio of BCMI-2 to strengthen my understanding of ARE (Section 5.6). As BCMI-2 was observed to be a suitable technical tool to support meditation practices, given time and resources, my next steps will be to initiate studies with scientific rigour to compare the effectiveness of different neurofeedback protocols and ARE parameters in inducing and maintaining different meditative states.

In addition to the main contribution, the technical BCMI-2 system, the research produced other creative outputs, including the following audio releases, software and public performances:

- 2016 *Compulsive Music Waves 1* | An audio release produced with BCMI-1's sequencer.
- 2016 *Compulsive Music Waves / Deciphering Addictions* | A collaborative installation produced with BCMI-1's sequencer.
- 2018 *Compulsive Music Waves 2* | An audio release produced with BCMI-1's sequencer.
- 2018 BCMI-1: NeuroSky-SuperCollider Interface | SuperCollider code of the first BCMI system developed in this research.
- 2019 *Aphorisms* by David Ryan | A performance using BCMI-2's code for transforming and spatialising acoustic sound.
- 2019 *Shamanic Soundscape – Neurofeedback Training Sessions* | An audio release featuring soundscapes generated in the NFT sessions testing BCMI-2.
- 2019 *Shamanic Soundscape – Level Two* | An audio release featuring stereo and surround sound files generated at my 2019 Cambridge Festival of Ideas performance, with an additional soundscape enhanced with binaural beats in post-production. Two soundscapes were also released on a physical CD in a Digipak case.
- 2019 Cambridge Festival of Ideas 2019 Performance Video 1 | A video collage of a screencast and two additional camera shots archiving my performance at the 2019 Cambridge Festival of Ideas.
- 2022 Cambridge Festival of Ideas 2019 Performance Video 2 | An alternative version of the above video, with additional binaural beats. The start of the video provides annotations clarifying the neurofeedback protocol used on theta at Fz.

While these creative outputs are not considered the main contribution to knowledge, as artefacts of practice research (Bulley and Sahin, 2021), they embody the richness of my work and expand its scope across and beyond disciplinary borders and outside academia. A complete list of creative outputs, including all research-related audio releases, presentations, demonstrations and studies, with URL links, can be found in Appendix 1.

The main contribution of this research is the creation of the BCMI-2 system and a number of recommendations based on the knowledge gained while developing and testing its suitability to support meditation practices in NFT and artistic performance settings. For researchers interested in meditation, BCMI-2 provides an affordable, research-grade system with customisable neurofeedback protocols and ARE parameters to be explored in NFT and artistic performance settings. My insights based on the knowledge gained while developing and testing the system can be found throughout this thesis and summarised in Chapter 6.

1.4 Research Question and Objectives

The research question and objectives that allow me to reflect on the main contribution of my thesis are as follows:

Research Question (RQ):
How can an affordable and open-source BCMI system be created to support meditation practices in NFT and artistic performance settings?

Research Objectives (ROs):
RO1: Conduct a literature review to find EEG correlates (neuromarkers) of meditative states and methods that can help induce and maintain these states.

RO2: Develop an affordable and open-source BCMI system based on the literature review findings.

RO3: Test the developed BCMI system's suitability to support meditation practices in NFT and artistic performance settings.

RO4: Based on the knowledge gained, provide recommendations for researchers interested in using BCMI-2 or developing new BCMI systems to support meditation practices in NFT and artistic performance settings.

I addressed RO1 with my literature review (summarised in Chapter 3), RO2 and RO3 by developing the two BCMI systems discussed in Chapters 4 and 5 and RO4 with my insights summarised in Chapter 6. Due to the practical nature of this research, addressing the research objectives did not follow a traditional waterfall project management methodology but instead utilised a more agile methodology that will be outlined in the next chapter.

Chapter 2

Methodology

2.1 Agile Project Management

To guide my practice research and address emerging questions and methods, I adapted ideas from agile project management (APM), a framework that transfers principles from agile software management to general project management (Drechsler and Ahlemann, 2015). While traditional waterfall project management focuses on one important outcome at the end of the project, APM produces cumulative outcomes by iterating the cycle of development stages. These cumulative outcomes can result in benefits throughout the process, not only for one project but also for other projects running parallel. As the iterative cycles of the projects running parallel during this research often informed each other, the flexibility of APM proved to be a practical method for managing the research overall (Fig. 2.1).

The non-linear and practical aspects of my research inquiry are captured in how Miranda (2014) outlines their approach to developing BCMI systems:

> Our approach is hands-on orientated. We often start by dreaming scenarios followed by implementing proof-of-concept or prototype systems. Then, as we test these systems, we learn what needs to be further developed, improved, discarded, replaced, and so on. These often lead to new dreamed scenarios and the cycle continues incrementally. In reality, . . . vision, practice and theory do not necessarily take place sequentially in our research.

The concept of practice research is commonly separated into two types: practice-based and practice-led. While practice-based creates an artefact that is the 'basis of the contribution to knowledge', practice-led 'leads primarily to new understandings about [the] practice' (Candy, 2006). However, as Bulley and Sahin (2021) state, these definitions and the interchangeable use of related terminology (e.g. 'creative arts research', 'practice-as-research') have often confused researchers. As established earlier, the main contributions of my research consist of the creation of the BCMI-2 system and my recommendations based on the knowledge gained while developing and testing its suitability to support meditation practices in NFT and artistic performance settings. Therefore, my research can be considered both practice-based (as

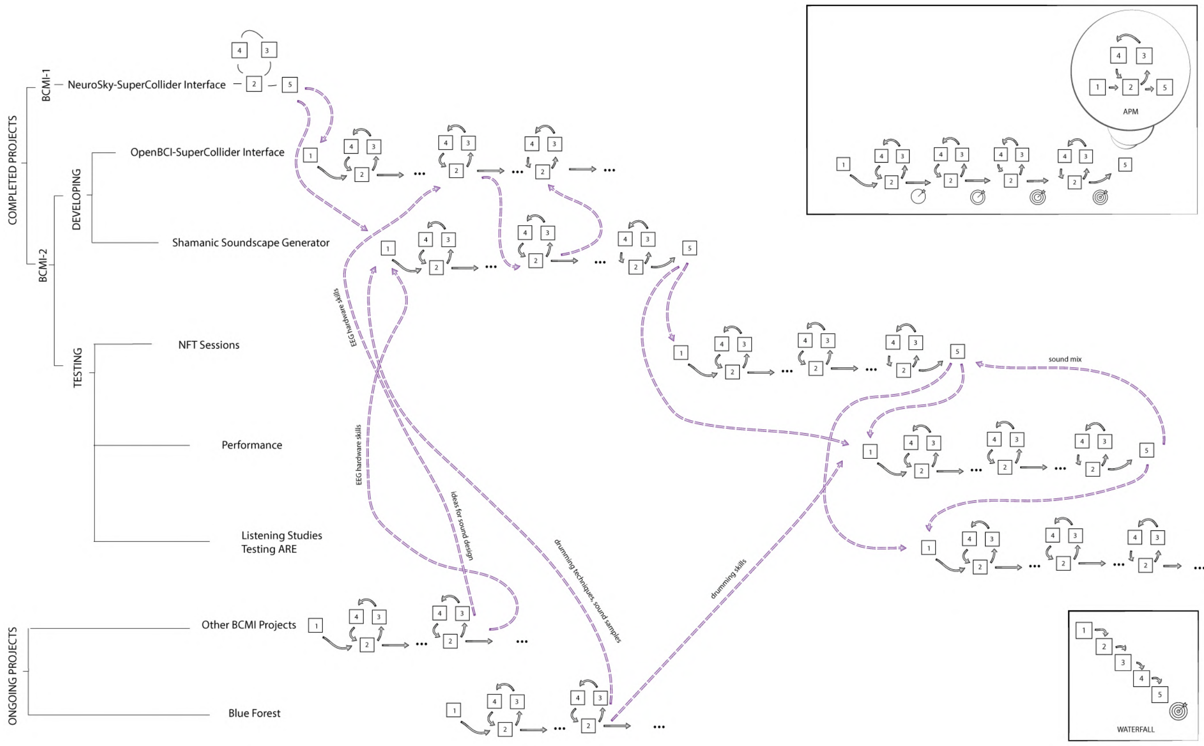

Figure 2.1: An illustration of the use of APM in my research. The large diagram (middle) depicts all of my research projects with examples of how they informed each other. The two smaller diagrams (top right and bottom right corners) contrast APM with traditional waterfall management, indicating the different stages and outcomes. An alternative layout of the projects can be seen at https://bcmi.khofstadter.com/timeline.

it created a proof-of-concept technical BCMI system) and practice-led (as it provides recommendations based on my new understanding of the practice). I used the following five APM stages in the BCMI-1 and BCMI-2 projects:

(1) Goals

During this stage, I used the RQ and the ROs, the relevant findings from the literature and the outcomes of previous or parallel-running projects to inform the project goals. I reviewed the literature using keywords through my university's digital search engine and Google Scholar and examined relevant publications. As each project had different goals, the keywords, publication date ranges and resource types in my searches were changed accordingly. Literature was often downloaded in the form of PDF files, which were then skimmed or scanned. Relevant information was highlighted and labelled with a continuously evolving list of tags, including the following:

#are, #art-science, #asc, #bci, #bci-art, #bci-science, #bci-sound, #consumer-grade, #eeg, #emotive, #engagement, #ibva, #immersion, #meditation, #muse, #music, #musification, #neurogame, #neuromarker, #neurosky, #nft, #off-line, #on-line, #openbci, #performance, #reseach-grade, #serious-gaming, #shamanism, #sonification, #sound, #sound-design, #substance-alternative, #supercollider, #surround-sound, #systematic-review.

(2) Design

In this stage, to help meet the project goals, I often drafted creative concepts (probable narratives) in a physical notebook with colour-coded drawings and text. I later fine-tuned these notes on the computer using Markdown language in Visual Studio Code (VSC) and Adobe Illustrator. Later in the research process, I organised my notes using the Zettelkasten – also called the Second Brain – method (Schmidt, 2016), which was provided by the Foam VSC extension (Ferretti and Eväkallio, 2020). Foam's non-hierarchical tagging and visualisation helped me see connections between the concepts in my notes.

(3) Development

This stage used prospective concepts that were established in the design stage. In some projects, I developed software for interfacing, and in others, the requirements for testing the developed software. In the listening study project, this stage resulted in the development of an accessible online survey.

(4) Testing

This stage consisted of testing the developed concepts. For instance, while BCMI-1 was tested informally by participants at my residence and at events where I demonstrated its use, BCMI-2 was tested in two types of formal settings: NFT and performance settings. In addition, my ARE that gradually decreases in tempo and rhythmic complexity was tested in the online listening study using SurveyMonkey. This study utilised SoundCloud's audio player without interactive audio (i.e. without using the neurofeedback protocol of the BCMI-2 system).

(5) Deployment

In this stage, in addition to analysing data from the testing stages to draw conclusions, I often demonstrated and presented my progress at public or academic events and published code on GitHub, music on Bandcamp and videos on YouTube. I also used OpenOffice and RAWGraphs to analyse the data collected with SurveyMonkey. The final deployment of the research consisted of generating this commentary, which was written in Markdown and exported to PDF with Pandoc's LaTeX converter.

Examples of APM cycles (also called sprints):

Here is a typical example of APM cycles in which, after the testing stage (4), parts of the project need to be redesigned (2), redeveloped (3) and retested (4) a few times before achieving an outcome:

APM stages 1,2,3,4,2,3,4,2,3,4,2,3,4,2,3,4,5, cumulative outcome, 1,2,3 …

What follows is an example in which the development stage (3) highlights issues in design (2), and hence, the project needs to be redesigned (2) before testing:

APM stages 1,2,3,2,3,2,3,4, …

Next is an example in which the design stage (2) highlights issues with the goals (1), which then need readjustment:

APM stages 1,2,1,2,3,4,5, cumulative outcome, …

2.2 Literature Review Method

In order to logically narrate my literature review in Chapter 3, I organised it thematically. However, to help articulate the research inquiry that has emerged in my practice, I will outline its chronological order in four stages:

1. Initial: before the start of the research
2. Exploratory: Autumn 2015 (start of research)—Summer 2018
3. Focused: Summer 2018—Summer 2019
4. Refined: August 2021—December 2021

Before I began this research, during my BA and MA studies in Creative Music Technology, I used the EEG hardware IBVA and NeuroSky with Max/MSP and SuperCollider software for artistic purposes (Hofstädter, 2009; 2013). After my MA, I wanted to gain a deeper understanding of the use of EEG with sound and apply this understanding beyond entertainment to help myself and others manage stress. This desire led me to conduct my **initial literature review**, in which I examined NFT and music therapy publications and discussed my initial ideas with key researchers in these disciplines. Amongst these researchers were Prof Jörg Fachner at the Cambridge Institute for Music Therapy Research, who later became my supervisor, Dr Tony Steffert, a London-based NFT practitioner with extensive knowledge regarding EEG sonification and Dr Eric Miller at Montclair University, author of *Bio-Guided Music Therapy* (2011). The initial literature review and subsequent discussions highlighted that there had been little investigation into the combined use of NFT and music therapy and that most software used in NFT primarily used visual feedback. Where the software used auditory feedback, it was old-fashioned. In other words, these systems did not employ modern software's many available techniques for mapping classified brain signals to sound control parameters. For example, in one of our early correspondences, Miller (2012) wrote:

> One of the reasons I wrote my book was that I also found that most NFT programs blatantly neglect the wide capabilities of audio and music, and I could find hardly any other works that attempted to integrate music and NF in more than just a basic manner.

Feeling encouraged, in my research proposal, I put forward to develop a new music-based invention, a BCMI system capable of utilising a wide range of compositional techniques for NFT that could strengthen many aspects of music therapy. First, NFT can make music-based inventions more interactive and engaging since users can not only see how their state of mind is affected by listening to music, but they can also affect the music with their state of mind in real time. Second, NFT can support music therapy's intangible experience with quantitative data from brain analysis. This proposal was the point of departure for this research.

This doctoral research began with an **exploratory literature review**, in which I continued the study of the domains of music therapy and NFT while extending its scope to others (e.g. meditation, spatial audio, serious gaming and, later, auditory entrainment). Parallel to this review, I was developing the BCMI-1 system by implementing ideas that emerged in this review (e.g. gaming elements for accumulative neurofeedback protocols and musical elements to support concentrative and receptive meditation). This stage of the research clarified that meditation was the method I wanted to explore for stress management and that I wanted to support meditation by combining a neurofeedback protocol inspired by Jeff Tarrant's work (Tarrant, 2017) and ARE inspired by Jeff Strong's work (Strong, 1998).

While further exploring these two methods in my **focused literature review**, I began addressing BCMI-1's limitation linked to its single, fixed EEG channel, by designing the multi-channel BCMI-2. Having a system that can record multi-channel signals from various locations on the head was important, as several neurofeedback protocols linked to enhancing meditation practices (including the NeuroMeditation protocols by Tarrant) use locations other than the forehead and more than one EEG channel. During this review, I completed the development of BCMI-2 with the idea of combining a neurofeedback protocol that would reward increased theta brainwaves with ARE that would gradually decrease in tempo and rhythmic complexity. I synthesised this idea through my literature review findings and discussions with Tarrant, Strong and several shamanic practitioners – all of which helped me become more experimental and intuitive in my drumming during my meditation practices. The system's suitability for supporting meditation was first demonstrated with two participants in NFT and later – as a natural progression – in an artistic performance setting. To further explore the ARE used in these settings, I conducted a listening study (Section 5.6) in which most participants experienced an increase in focus (67%) and recalled being at their most focused state towards the end of the soundscape. In this proof-of-concept research, this outcome does not contribute to scientific knowledge with evidence on the effectiveness of the ARE that gradually decreases in tempo and rhythmic complexity. It only strengthens my understanding of, and trust in, the potential of ARE in supporting meditation. In order to provide scientific evidence for the effectiveness of different ARE and neurofeedback protocol parameters and their combinations, I plan to conduct more studies with scientific rigour.

Finally, I conducted my **refined literature review** to help better situate my main contribution to knowledge. This review enabled me to provide a brief overview of the use of BCMI in artistic performance and academic research settings and describe the related classifications for sonification and musification with active and passive user control. This stage also helped refine my RQ and ROs so that they better reflect my main contribution.

Throughout the years, my research has undergone numerous changes and has turned out to be more complex than I envisioned initially. Still, I think the overall approach was effective; it resulted in a stable BCMI system that can be used to support meditation practices in two different settings. Furthermore, I hope my experience, as outlined in this written commentary, will help researchers better understand the interdisciplinary processes involved in developing BCMI systems for meditation.

Chapter 3

Literature Review

3.1 Brain-Computer Interfacing (BCI)

3.1.1 Introduction

In the field of BCI, a subdomain of HCI, BCI systems, also referred to as brain–machine interfaces or mind–machine interfaces, allow for non-muscular, real-time interaction between the human brain and machines (Fig. 3.1). What the received information is and how it is processed on both sides of this closed-loop interaction are essential to the success of BCI applications (Daly et al., 2014).

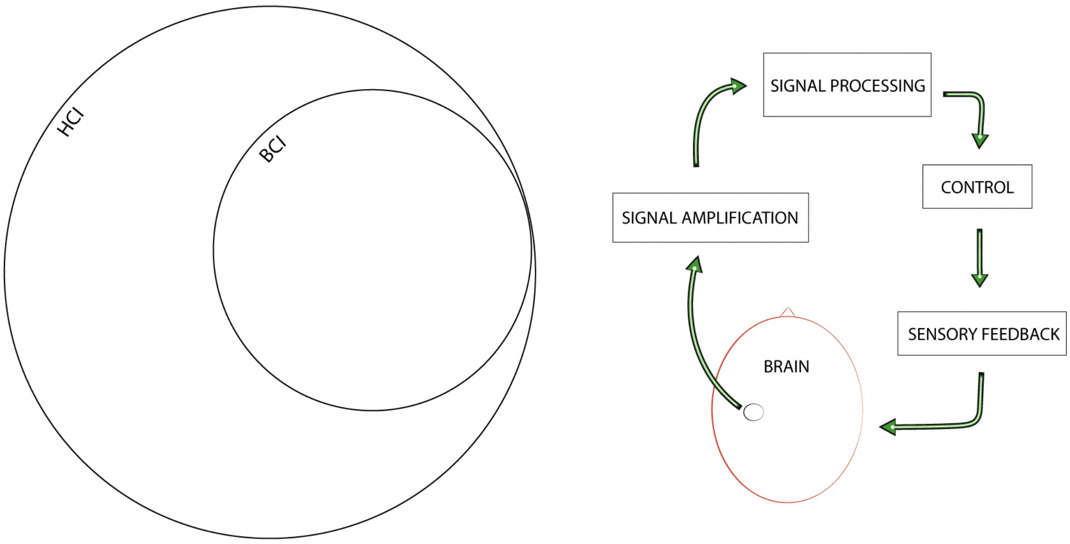

Figure 3.1: Venn diagram depicting BCI as a subdomain of HCI (left) and an outline of the steps of a real-time BCI loop (right). The loop begins with amplifying brain signals, progresses through signal processing and then advances to control and sensory feedback before going back to the brain.

3.1.2 Applications and classifications

BCI systems consist of both hardware and software parts and are often designed for specific applications. In their systematic review, Mridha et al. (2021) classify BCI applications based on usability as biomedical or non-biomedical. Biomedical applications can access and diagnose central nervous system (CNS) functions lost through sickness or by trauma and functions linked to enhancing the cognitive abilities of healthy people. In addition to assessment, applications are also used to repair (Hara, 2015), replace (McFarland and Wolpaw, 2008) or enhance functions (Gruzelier, 2018; Ehrlich et al., 2019; Daly et al., 2020; Hunkin, King and Zajac, 2020) in their respective clinical or non-clinical settings. While many non-biomedical applications are recreational, such as those in gaming (Kerous, Skola and Liarokapis, 2017; Cattan, 2021) and artistic performance settings (Nijholt, 2019), some applications are also used in domestic smart-home settings (Laport López, 2022; Nijholt et al., 2022) and in industry — for instance to increase the safety of people working on demanding tasks (Zhang, Wang and Fuhlbrigge, 2010; Binias, Myszor and Cyran, 2018). While BCI systems are often designed for one specific application, some systems can be used for multiple applications (e.g. bio-medical ability-enhancing and non-biomedical recreational applications). For example, the domain of BCMI (detailed in Section 3.6), has numerous applications enhancing an ability while performing music (Fig. 3.2).

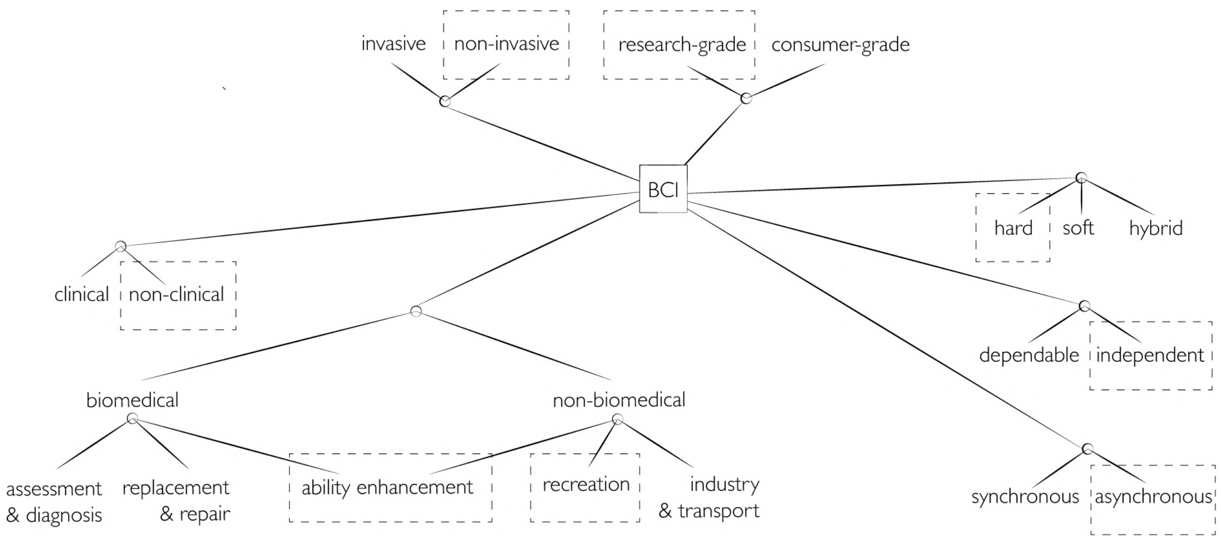

Figure 3.2: A tree diagram visualising on-line BCI classifications based on invasiveness, grade, interfacing, dependability, synchronisation and usability. The dotted lines indicate how the BCMI-2 system developed in this research can be classified. 'Ability enhancement' is linked to my project that tested this system's suitability in NFT, and 'recreation' is connected with my artistic performance setting.

While all clinical applications are biomedical, non-clinical applications can be bio-medical or non-biomedical (Nijholt et al., 2022). For instance, the biomedical application of NFT can be used in clinical settings to move clients' brain functions away from clinical and towards normative, and in non-clinical settings to enhance certain abilities of healthy people. BCI systems can be non-invasive, in which electrodes record brain activity outside the skull, or invasive, in which electrodes are implanted inside the skull using surgery. While the key function of BCI is to provide real-time (on-line) interaction between human brains and machines, the software parts of some systems can often be used for non-real-time (off-line) signal processing as well (e.g. to visualise or sonify brain signals with scientific or more artistic purposes). BCI can also be categorised as hard, soft or hybrid:

- In hard (active) systems, the control parameters are based on operant conditioning providing positive or negative feedback on users' conscious efforts. This type is often referred to as explicit BCI with active control. An example of hard BCI is motor imagery, in which the user performs a mental task to control an external device.
- In soft (passive) systems, the control parameters are based on machine-learning. The system learns and optimises the interaction between the user and the computer. This type is often referred to as implicit BCI with passive control.
- Hybrid systems use both hard and soft methods.[1]

Krol, Andreessen and Zander (2018) clarify passive systems:

> [The] use of the word 'passive' here results from a user-centred perspective on HCI. It refers to the role of the end user of a system with respect to the BCI: the underlying signals being automatic, spontaneous brain activity, it is an inherent and defining aspect that the user exerts no effort to actively, explicitly, or voluntarily elicit or modulate this activity. Instead, the user focuses on the task at hand while a passive BCI system, in the background, monitors their brain activity for informative correlates of relevant cognitive or affective states.

BCI systems can also be research- or consumer-grade, with the latter sometimes being referred to as 'off-the-shelf' or 'low-cost' systems. While clinical applications generally use expensive research-grade systems certified for medical purposes, other biomedical and non-biomedical applications can use either. For instance, non-biomedical applications of BCI in recreational settings have used research-grade (Eaton and Miranda, 2013a) and consumer-grade systems (Rosenboom and Young, 2015). However, while the most popular applications of consumer-grade systems support meditation, relaxation, and other ability-enhancing practices (and, more recently, gaming in non-clinical settings), their potential for clinical research has also been evaluated (Ratti et al., 2017; Lau-Zhu, Lau and McLoughlin, 2019; Vasiljevic and Miranda, 2019; Sawangjai et al., 2020; Kawala-Sterniuk et al., 2021).[2] A BCI system can be classified as independent when users have some level of motor control or as dependent, for instance, when users are severely disabled. The interaction between a BCI system and a brain can also be synchronous or asynchronous. Interaction is synchronous when users are required to perform a specific cognitive activity at a particular moment in time. It is asynchronous when they are free to perform activities at any time (Ramadan and Vasilakos, 2016).

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[1] The term 'hybrid' can also refer to a system that measures not only neurological signals but other physiological signals as well, e.g. as in Daly et al. (2020).

[2] The advantages and disadvantages I discovered by developing two systems, BCMI-1 with consumer-grade NeuroSky and BCMI-2 with research-grade OpenBCI, are discussed in Chapter 5.

3.1.3 Interfacing steps with EEG

Several methods can measure brain activity: EEG, electrocorticography (ECoG), single-neuron recordings, magnetoencephalography (MEG), positron emission tomography (PET), functional magnetic resonance imaging (fMRI) and functional near-infrared spectroscopy (fNIRS). According to Ramadan and Vasilakos (2016), while it is ECoG, single-neuron recordings and EEG that are considered valid methods for BCI systems based on cost, quality of communication and the available number of control channels, the most common method is EEG due to its ease of use, security and affordability. Also, out of these three methods, only EEG is non-invasive.

In essence, in real-time BCI with EEG, the electrical fields on the scalp are measured with sensitive electrodes and then sent to a hardware device that amplifies these signals. Next, the amplified signals are processed with analogue or digital signal processing (DSP) on this hardware or later with software on a computer. These signal processes involve noise reduction, feature extraction and classification. Finally, classified features are mapped to control parameters, such as the movement of a robotic arm (McFarland and Wolpaw, 2008) or the algorithms in computer-generated music (Daly et al., 2020). This process is depicted in Fig. 3.3 and further detailed below.

Figure 3.3: BCI steps with EEG.

(1) electrical fields - The electrical activity generated by the biological brain cells, the neurons, are measured as analogue signals by sensitive electrodes. It is the specific application of the BCI that informs the number of electrodes needed and their locations on the head. Some systems record only one or two channels, some 10 (Fig. 3.4), while others record above 100.

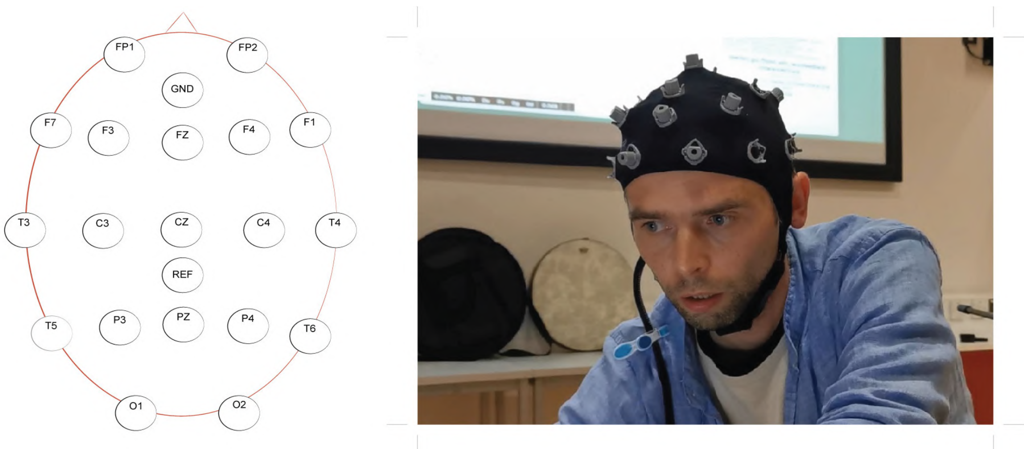

Figure 3.4: EEG electrode placements with the 10-20 system available on the Greentek gel-free cap used with the BCMI-2 system (left) and a photo of this cap on my head recording eight active electrodes (right). Caps can read pre-frontal (Fp), frontal (F), temporal (T), parietal (P), occipital (O), and central (C) areas of the brain.

(2) amplification and conversion - The analogue signals from the electrodes are received on the EEG hardware, where they are amplified and digitalised. Systems can use research- or consumer-grade hardware for EEG amplification and analogue-to-digital (A/D) conversion. Some hardware send the digital signals to a computer for further processing, while others perform specific processes (e.g. noise reduction, feature extraction, and classifications) still on the hardware, as do NeuroSky headsets used with my BCMI-1 system, for instance.

(3) noise reduction - The amplified and digitalised signals (the raw EEG signals) are cleaned of user- and system-related artefacts. While systems often attenuate frequencies below 1 Hz and above 50 Hz with a bandpass filter and frequencies of the mains hum with a notch filter, numerous other methods have been used to remove artefacts (e.g. muscle movements and eye blinks), some of which involve machine-learning techniques (Lai et al., 2018).

(4) feature extraction - The cleaned raw signals are analysed for recognisable patterns, e.g. in the amplitude domain (event-related potential (ERP), peak latency, zero-crossing), the frequency domain (band power fast Fourier transform (FFT), power spectral density, phase coherence, complex networks) or with a combinatorial method, i.e. a combination of some of these techniques.

(5) classification - Patterns extracted are organised to application-specific meanings (e.g. increased low-alpha indicating relaxation or increased high-beta stress). Classification is also referred to as 'feature translation' (Mason and Birch, 2003).

(6) mapping - The variables storing classified data (meanings) are linked (mapped) to application-specific control parameters.

(7) control parameters - The now brain-controlled parameters are application-specific activities (e.g. robotic arm movements or carrier frequency changes in a sound synthesiser).[3]

Besides the earlier cited publication by Mridha et al. (2021), I found the reviews by Kawala-Sterniuk et al. (2021) and Ramadan and Vasilakos (2016) also informative.

3.2 Neurofeedback Training (NFT)

3.2.1 Introduction

Besides BCI, HCI offers a range of other methods to map biological signals to feedback to help improve mental or physical conditions. The signals often used in these biofeedback systems are heart rate variability (HRV), electromyogram (EMG), electrodermal activity (EDA) and EEG (McKee, 2008), with the latter often called EEG biofeedback, neurofeedback or neurofeedback training. While the terms 'neurofeedback',

[3] Ways in which brain signals mapped to sound have been used in artistic and academic settings since the 1960s is detailed in Sections 3.6 and 3.7. How my BCMI-2 system used sound with a neurofeedback protocol to entrain (reward) theta brainwaves is discussed in Section 4.2.2.

‘neurofeedback training’, ‘neurofeedback therapy’, ‘neuro therapy’, ‘neuro-biofeedback’ and ‘brainwave biofeedback’ have been used fairly interchangeably in the literature, the most commonly used terms are ‘neurofeedback’ and ‘neurofeedback training’. As ‘neurofeedback’ technically does not necessarily imply training, in this thesis, I use ‘neurofeedback training’ (NFT) to refer to the practice in which BCI systems provide feedback on neurological activity to trainees for a specific length and regularity of time defined by trainers in clinical or non-clinical settings. To yield anticipated progress, the trainers decide how long sessions should last and how often sessions should be held. After initial assessments, sessions usually last 20 to 30 minutes and are held 10 to 20 times. Also, to avoid ambiguity, I will refer to the technique of mapping classified brain activity to control parameters in real time with the term ‘neurofeedback protocol’ instead of with the more umbrella term ‘neurofeedback’ (Fig. 3.5).

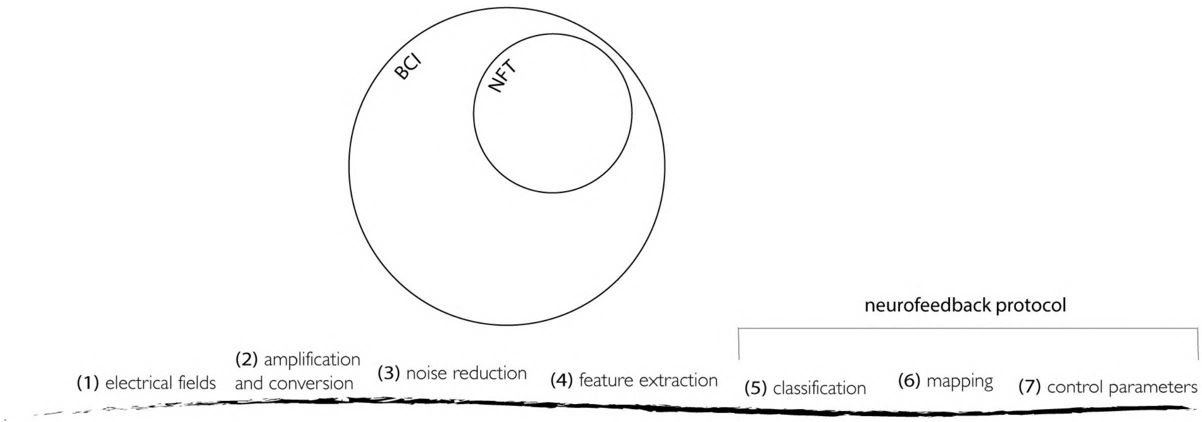

Figure 3.5: Venn diagram (top) illustrating the field of NFT as a part of BCI and an outline of the BCI steps (bottom) handled by the neurofeedback protocol.

Also, because NFT can use EEG, fNIRS (Kohl et al., 2020) or PET (Ros et al., 2021), the most accurate term to describe the NFT explored in my research could be ‘real-time EEG NFT’. Suggestions to refine terminology can be found in Swingle (2021). The International Society for Neuroregulation and Research (ISNR) defines NFT as follows:

> Like other forms of biofeedback, NFT uses monitoring devices to provide moment-to-moment information to an individual on the state of their physiological functioning. The characteristic that distinguishes NFT from other biofeedback is a focus on the central nervous system and the brain. NFT has its foundations in basic and applied neuroscience as well as data-based clinical practice. It takes into account behavioral, cognitive, and subjective aspects as well as brain activity (ISNR, 2022).

The success of NFT, and many other BCI applications, relies on neuroplasticity, the brain’s ability to advance its neural networks on two levels: (1) on a functional level by strengthening or weakening existing synaptic connections and by creating new connections and (2) on a structural level by changing existing neural pathways and creating new pathways. Although the concept existed previously, the mature brain was believed to have a fixed structure until the 1960s, when neuroscientific discoveries began proving that the brain’s structure can change after maturity. Costandi (2016) provides a detailed overview of the history of neuroplasticity, highlighting key findings and methods.

3.2.2 Applications and classifications

Since Joe Kamiya's first experiments training college students to control alpha brainwaves in the 1960s (Kamiya, 2019), NFT 'has become the most widely applied psychophysiological procedure enabling individuals to self-regulate specific characteristics of the EEG' (Mirifar, Keil and Ehrlenspiel, 2022). According to two recent and comprehensive bibliographies listing research of the field (Applied Psychophysiology Education, 2021; ISNR, 2021), NFT has been explored in a range of clinical and non-clinical settings. In clinical settings, to address an illness or symptom with clinical relevance, including attention deficit disorders, anxiety, autism, chronic pain, depression, epilepsy, substance abuse and post-traumatic stress disorder, and in non-clinical settings to enhance healthy people's ability in the areas of sport, mood and cognitive enhancement as well as in performing arts.

While the key function of NFT systems is to provide feedback to users in real time, the same system often also archives the raw brain data in files for later, off-line processing. These off-line processes could be carried out on the same NFT system or on other systems providing additional, perhaps more advanced DSP tools. NFT sessions can also be video recorded, which, when replayed together with the brain signal, can help, for instance, to align movements contaminating signals or closed eyes raising alpha brainwaves.[4]

Clinical settings can only be facilitated by trainers who are licensed clinicians, such as medical doctors, psychologists or occupational therapists. In contrast, non-clinical settings can be facilitated without these licences (e.g. by trainers described as neurofeedback coaches). Also, with BCI systems becoming more affordable, user friendly and customisable, even users themselves can become their own trainers in their own homes (e.g. by using consumer-grade NeuroSky or Muse systems). However, this irregularity can become problematic, as pointed out by Swingle (2021):

> The result is that too often neither the public nor otherwise very qualified professionals can tell the difference between the bona fide research practitioner, the trained practitioner, the naive (insufficiently trained) but otherwise well-intended practitioner, the fully ignorant, and the spurious business person. . . . Despite professional associations and certification bodies such as AAPB, ISNR, BFE, BCIA, and IQCB[5], in 2021, the field is still largely unregulated, and our scope of practice remains fully reliant upon complementary competence.

Although NFT has begun to attract the attention of the scientific and medical mainstream (Ros et al., 2020), due to the above-described irregularities, as Swingle (2021) put it, valid and invalid criticism has also surfaced. Systematic reviews, while acknowledging the effectiveness or potential of NFT, have provided similar recommendations for improvement, including the need for more randomised control trials and larger samples sizes (Panisch and Hai, 2018; Patel et al., 2020; Steingrimsson et al., 2020; Baena et al., 2021; Hesam-Shariati et al., 2021; Trambaiolli et al., 2021), more optimal treatment protocols for

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[4] While testing BCMI-2 (Sections 5.4 and 5.5), I archived brain data to be analysed later with BCMI-2's plotter function and recorded screencasts that captured users while meditating.

[5] Association for Applied Psychophysiology and Biofeedback, Inc. (AAPB), International Society for Neuroregulation and Research (ISNR), Biofeedback Federation of Europe (BFE), Biofeedback Certification International Alliance (BCIA), International QEEG Certification Board (IQCB).

trainers (Hoogdalem et al., 2021), revised method classifications (Gong et al., 2021), methods to identify trainees who are unlikely to benefit from NFT prior to the actual training (Alkoby et al., 2018) and implementation of unified reporting and experimental design standards (Ros et al., 2020).

3.2.3 EEG neurofeedback protocols

NFT addresses different goals with different neurofeedback protocols, each with specifically designed mappings between classified brain data and control parameters. For instance, alert, focus and peak protocols are commonly used when treating attention deficit disorders, a relax protocol when addressing anxiety and a deep protocol for personal exploration (Collura, 2017). Most NFT systems extract the frequency spectrum from the raw EEG signal with either digital filters or FFT, then classify characteristics of selected frequency bands in line with the training goals and then map this classified data to the control parameters (e.g. auditory or visual feedback). The most commonly defined frequency bands, also called brainwaves, can be seen in Fig. 3.6.

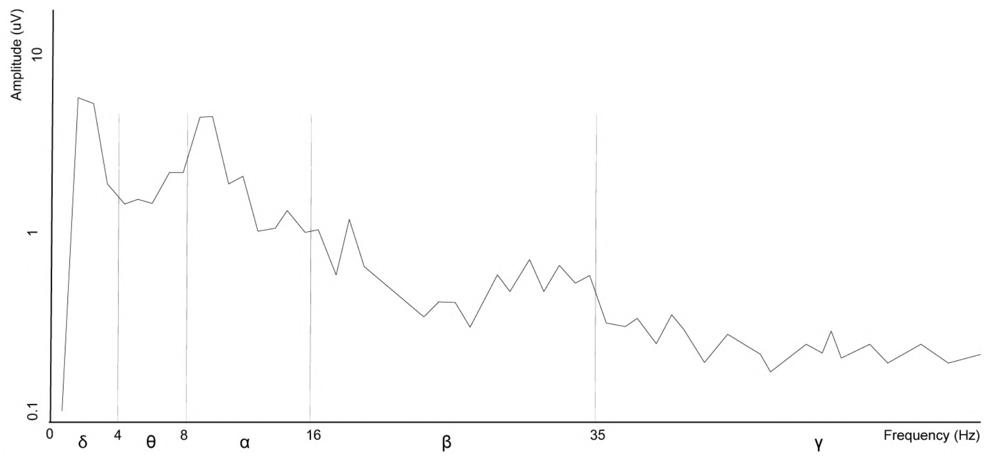

Figure 3.6: An FFT plot of a one-channel EEG signal separated into brainwaves: delta (δ) between 0-4 Hz, theta (θ) between 4-8 Hz, alpha (α) often divided as low-alpha (alpha1) between 8-12 Hz and high-alpha (alpha2) between 12-16 Hz, beta (β) often divided as low-beta (beta1) between 16-20 Hz; mid-beta (beta2) between 20-30 Hz and high-beta (beta3) between 30-35 Hz and gamma (γ) between 35-45 Hz.

In general, while all these frequency bands are active in ordinary waking consciousness, strong (high relative amplitude) delta is linked to sleep and the unconscious mind, strong theta to deep relaxation, meditation, trance and hypnosis, and access to unconscious materials. Strong alpha is linked to wakeful relaxation, increased self-awareness and focus, strong beta to alertness and active thinking and even stress or intense mental activity and strong gamma to simultaneous processing of information from different brain areas (Kawala-Sterniuk et al., 2021). In addition to these frequency bands, neurofeedback protocols can also use ERPs (Kropotov, Mueller and Ponomarev, 2011), features extracted with z-score (Thatcher and Lubar, 2014; Collura, 2017, pp.154–179), low-resolution brain electromagnetic tomography (LORETA) and synchrony (Collura, 2017, pp.180–183) methods, etc.

A typical mapping technique is to set thresholds for the classified data. These thresholds are often called indicators or inhibitors. An indicator rewards the user when classified data moves above a threshold, and an inhibitor rewards when classified data stays below a threshold (Fig. 3.7). Protocols can also have multiple thresholds and rewards when multiple conditions are met (Fig. 3.8). Thresholds are usually set by the trainer manually at the beginning of a session and adjusted manually during this session. However, with some modern software, automatic thresholding, where the software adjusts the thresholds to the ongoing success of the training, can also be used (Dhindsa et al., 2018).

Collura (2017, p.184) suggests that feedback (the control parameter) must be accurate, timely, meaningful and aesthetic. It needs to be mapped to classified signals derived from accurate EEG readings and signal processing. The timing of the feedback needs to be immediate, especially when training fast brainwaves (beta, gamma), to allow temporal binding, the brain's ability to link separate events into one piece of meaningful information. Feedback also needs to be aesthetic so that the brain aims to receive it as a positive reward, something to seek. While most feedback is visual on a computer screen, it can also be auditory (Steffert, 2018), haptic (Shabani et al., 2021) or coming from real-world devices (Neuper and Pfurtscheller, 2009).

Auditory feedback can use short (discrete) and continuous sounds. While short sounds are often played when classified signals move beyond indicators or inhibitors, continuous sounds are often mapped to classified signals to provide uninterrupted feedback (e.g. when the amplitude of an alpha brainwave is mapped to the amplitude of a sound). Auditory feedback can be synthesised in real time or be played back from pre-recorded audio samples. While there are BCI systems that use brain signals to generate not only music in real time but also music that can help induce desired emotional (affective) states (Ehrlich et al., 2019; Daly et al., 2020), music used as a control parameter is more often a pre-recorded composition. For instance, in the 'musical neurofeedback' of Ramirez et al. (2015), elderly people suffering from depression controlled the tempo and loudness of audio files containing music chosen by these users themselves. In the 'music-based auditory neurofeedback' by Takabatake et al. (2021), trainees needed to increase the power of their alpha brainwaves to minimise the volume of white noise superimposed onto classical music played back from an audio file. In Fedotchev, Radchenko and Zemlianaia (2018) and Fedotchev et al. (2021), trainees are rewarded with a volume increase on a file playing a famous classical music piece. NeuroMeditation protocols (Tarrant, 2020), discussed shortly in more detail, also increase the volume of pre-recorded music to reward trainees. The reasons for generative music not being applied widely in NFT is likely due to trainers not having the complementary expertise and skillsets required (e.g. music theory and computer science), that make algorithmic music challenging to implement into BCI systems or due to trainers being sceptical about the effectiveness of music generated by algorithms over music composed by humans regarding how they can affect mental states.

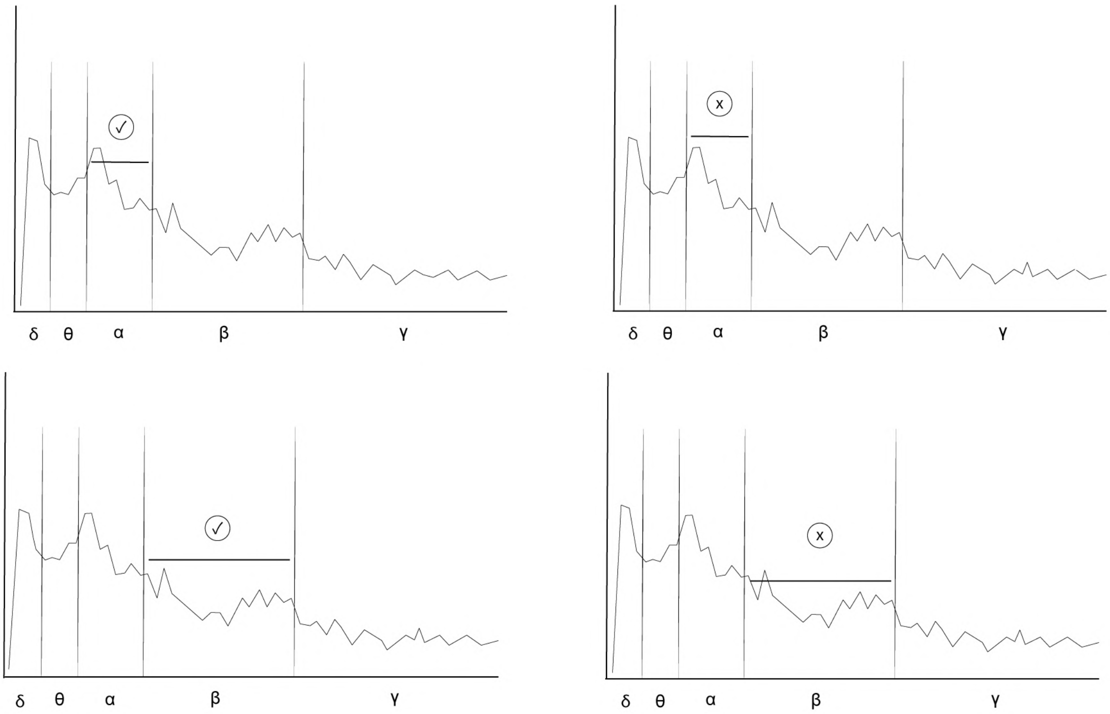

Figure 3.7: One-channel neurofeedback indicator and inhibitor plots. An indicator rewards (top left) and does not reward (top right). An inhibitor rewards (bottom left) and does not reward (bottom right).

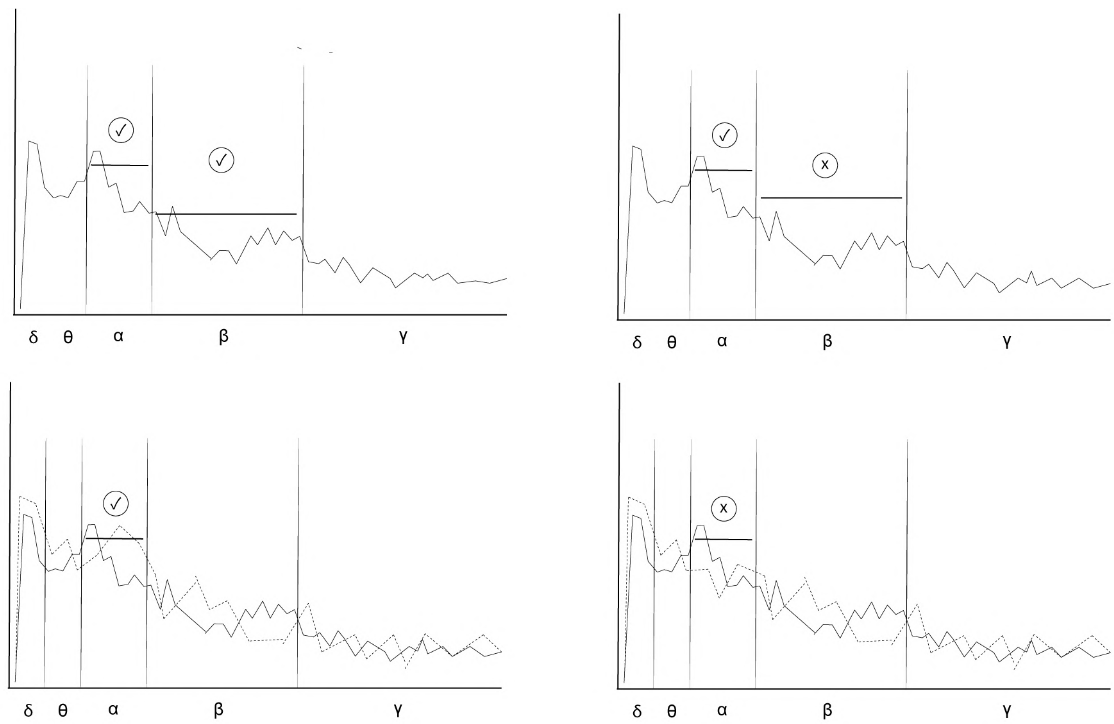

Figure 3.8: Two-channel neurofeedback indicator and inhibitor plots. Two indicators reward (top left) and do not reward (top right). One indicator used on two signals rewards (bottom left) and does not reward (bottom right).

3.2.4 Examples of standard neurofeedback protocols

Collura (2017, p.147) outlines some standard neurofeedback protocols. An alert protocol (Fig. 3.9) inhibits theta and rewards increased high-beta generally on C3 or Cz. It is often called 'beta training' and is used to help people with attention deficit disorder (ADD) and attention deficit hyperactive disorder (ADHD). A sharp protocol (Fig. 3.10), a type of squash protocol, inhibits brainwaves from 4 to 20 Hz, usually on Cz, to create optimal readiness before performing a particular task (e.g. hitting a ball in golf or shooting an arrow in archery). Synchrony protocols (Fig. 3.11) commonly train relaxation-related alpha inter-hemispheric and intra-hemispheric synchrony or clarity-related gamma synchrony in more recent studies. Metrics extracting synchrony between signals include (1) pure coherence measuring phase separation, (2) training coherence measuring zero phase separation and similar amplitudes, (3) spectral correlation measuring similar spectral energy, (4) comodulation measuring similar amplitude variations and (5) phase measuring phase coherence. Finally, a deep protocol (Fig. 3.12) is a type of alpha-theta protocol that rewards increased alpha and theta brainwaves on Pz to help move trainees into relaxed states. It is used to help drug abusers overcome addictions, and healthy individuals create internal change in personal explorations.

> During an alpha/theta session, there is an event called 'crossover' that is expected some time into the session. At this point, whereas the alpha is generally the largest rhythm, theta becomes the dominant rhythm. It appears that at this point, the alpha magnitude drops, leaving the theta as the largest component. It is when the client is in this crossed-over condition that the hypnagogic state occurs (Collura, 2017, p.134).[6]

This hypnagogic state — also called hypnagogia — is described by Gruzelier (2018) as 'the reverie or twilight state between waking and sleeping'. When comparing alpha-theta to sensorimotor rhythm (SMR) and low-beta training, Gruzelier (2008) found that an alpha-theta protocol rewarding the 'crossover' was the most useful for enhancing the performance of elite and novice musicians. His specific alpha-theta protocol rewarded increased theta over alpha by raising the volume of a pleasant soundscape featuring waves crashing on the shore and sensual gong sounds. A detailed review of his research with a variety of neurofeedback protocols designed to enhance the performance of musicians, dancers and actors as well as schoolchildren can be found in Gruzelier (2014a; 2014b; 2014c) and in his more recent overview (Gruzelier, 2018), all providing an excellent source of methodologies and recommendations for those interested in using NFT for cognitive enhancement.

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[6] This 'crossover' is also referred to as the 'breakthrough' (Washburn, 1978). To test the suitability of my BCMI-2 system for meditation practices in NFT and artistic performance settings, I explored a hypnagogic state called the SSC. My use of a neurofeedback protocol rewarding increased theta at Fz in addition to ARE is outlined in Section 5.2.2.

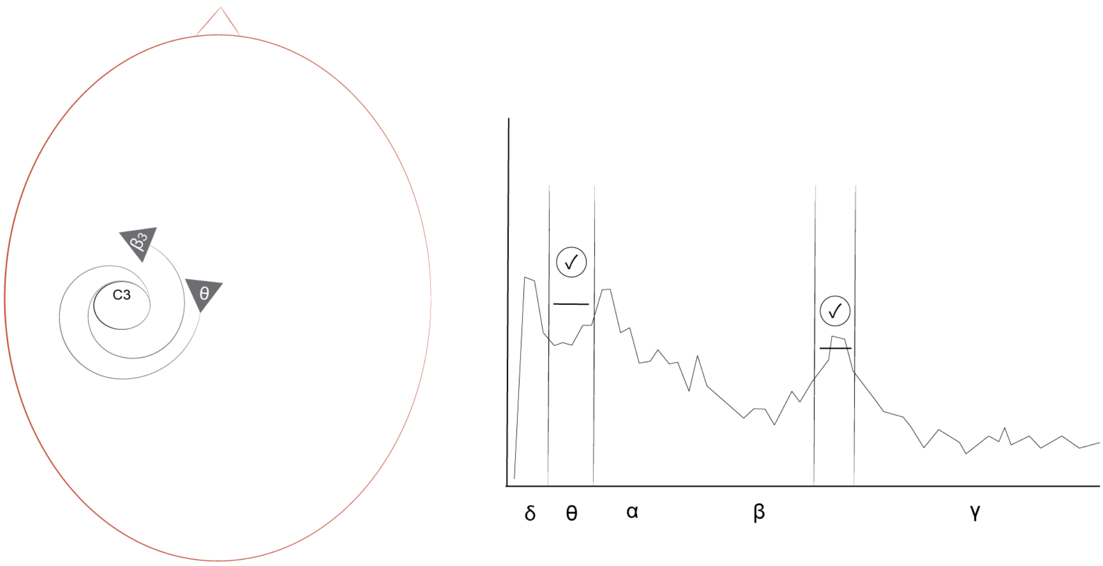

Figure 3.9: An alert protocol's electrode location (left) and spectral plot (right) show the application of one inhibitor applied on theta and one indicator used on high-beta.

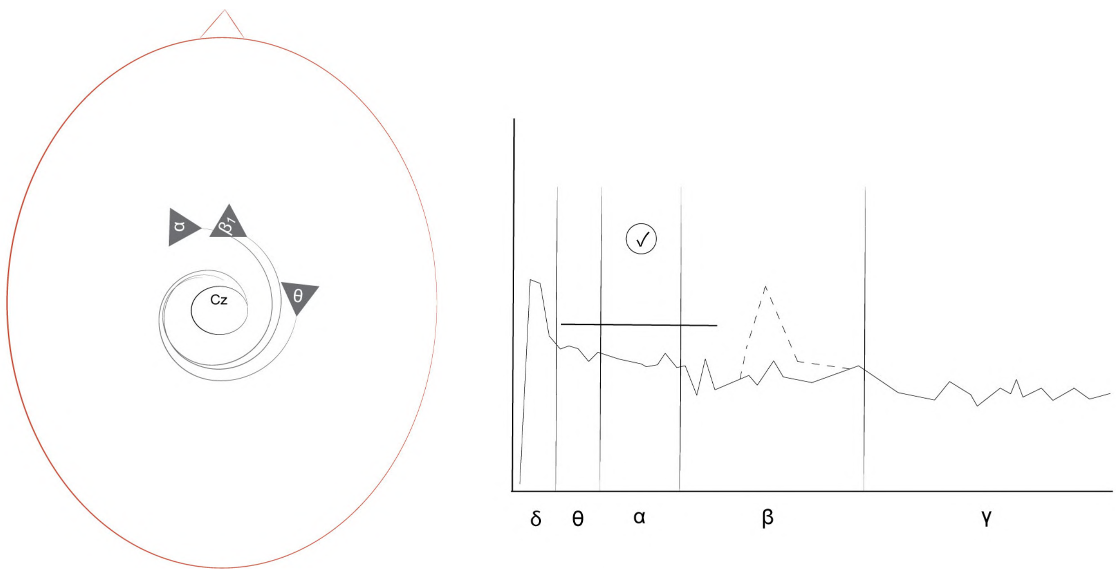

Figure 3.10: A sharp protocol's electrode location (left) and spectral plot (right) show the application of one wide inhibitor between 4-20 Hz. The peak with the dotted line indicates the brain activity of the particular task performed.

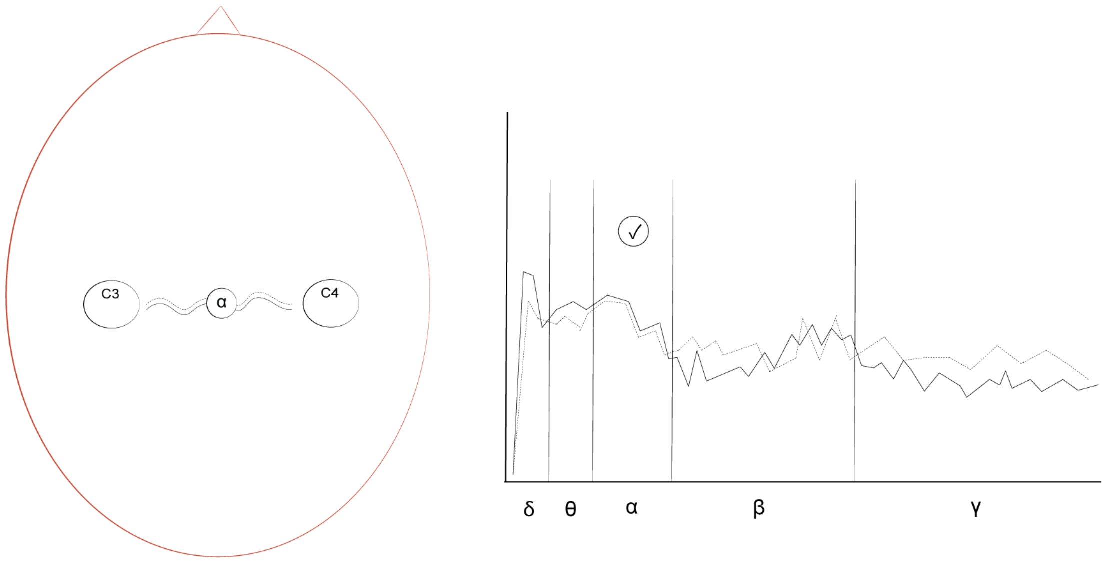

Figure 3.11: An alpha-phase synchrony protocol's electrode location (left) and spectral plot (right) show reward given when alpha between C3 and C4 are in phase.

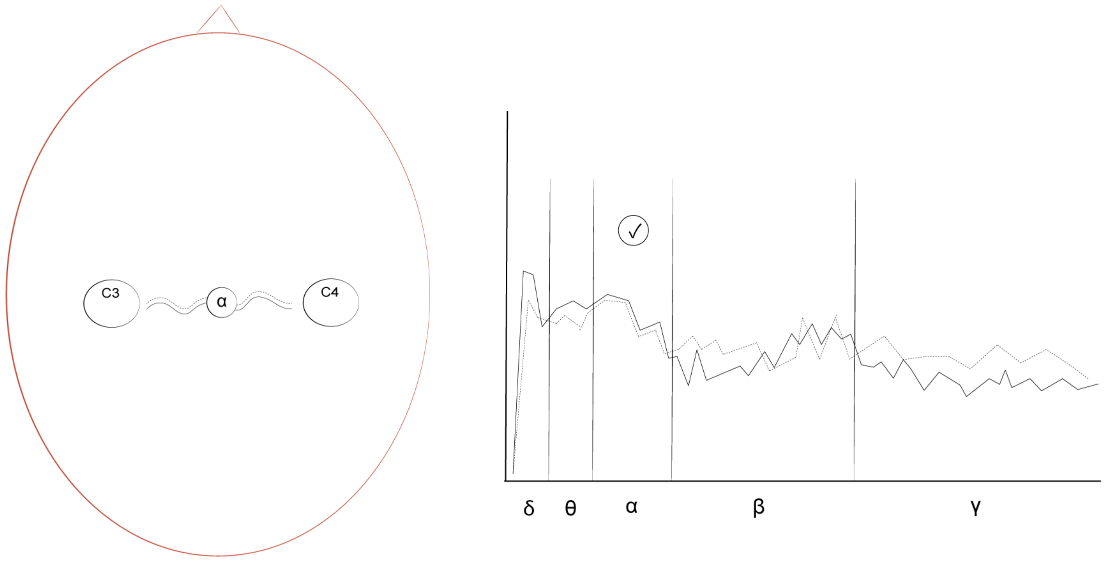

Figure 3.12: A deep protocol's electrode location (left) and spectral plot (right) show the application of two indicators, one on theta and one on alpha.

3.3 Meditation with NFT

3.3.1 Meditation

Meditation is a set of mind-body practices that, by regulating attention, can help induce a variety of physiological and mental changes that range from simple relaxation to dramatic mystical experiences. Its methods include different practices, e.g. breath-work (Holmes et al., 1996; Bing-Canar, Pizzuto and Compton, 2016), visualisation (Margolin, Pierce and Wiley, 2011) and repetitive mantras (Lynch et al., 2018). While some consider meditation to originate from shamanism in the Stone Age (Monaghan and Viereck, 1999), more commonly, it is believed to have emerged from religious and spiritual practices 'originally developed by and for religious women and men who lived within monastic contexts or at the margins of society' (Farias, Brazier and Lalljee, 2021). While we cannot precisely define when and where meditation began, we know that Buddha in India, Lao-Tze in China, and Dosho in Japan were the leading advocates of its use in the East. Although meditation has also been practised in Judaism (Storedalen, 2013), the ancient Islamic tradition of Sufism (Jamal, 2013) and Christianity (Casiday, 2013), only after the more recent translations of Eastern texts to European languages has it become more widespread and later secularised in the West, e.g. by the works of Jon Kabat-Zinn on mindfulness meditation (Kabat-Zinn, 2003). Throughout history, the definitions and practices of meditation have changed in line with how cultures have used it for their religious and spiritual practices (Bronkhorst, 2014). Over the last few decades, as meditation became more secularised, it has also become of interest to the research community for its positive effects on general well-being (Heppner and Shirk, 2018) and serious health issues (Grossman et al., 2004; Rubia, 2009; Kwon et al., 2021; May and Maurin, 2021).

The theoretical study by Washburn (1978) separates meditation into two main types; concentrative and receptive (Fig. 3.13).

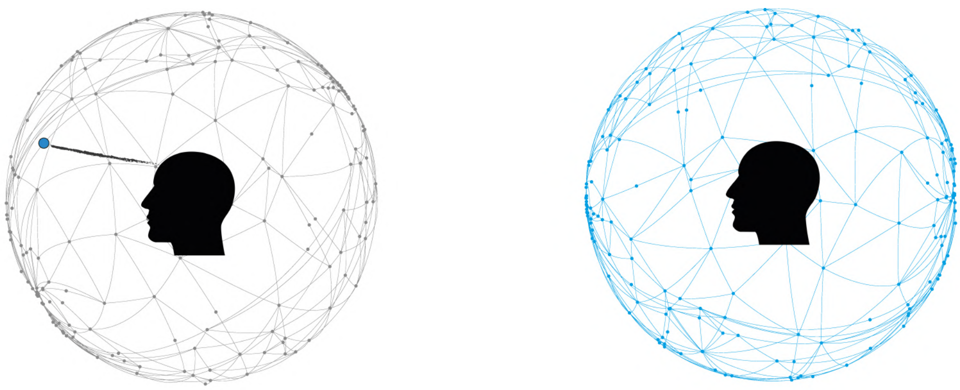

Figure 3.13: Visual interpretation of concentrative (left) and receptive (right) meditation. The colour blue indicates the object of focus.

Concentrative meditation focuses on one object while trying to neglect all other objects. This one object can be external or internal, for instance, the flame of a real or an imaginary candle. While concentrating on the selected object, the state of mind is constantly shifting sometimes until a breakthrough — the crossover

— where the meditator becomes absorbed in the object. This absorption has been referred to as 'samiidhi' in Hinduism, 'jhana' in Buddhism and 'enstatis' in contemporary research on yoga. Receptive meditation is a more passive method of paying attention to internal or external objects. Attention is not fixed on any object specifically for an extended period; rather, objects are first acknowledged and then maintained with passive attention. With this technique, the meditator can pay attention to several objects simultaneously. Receptive meditation is associated with mindfulness ('satipatthana') and insight ('vipassana') meditations in Buddhism, just-sitting ('ishikan-tazat') in Zen-Buddhism, choice-less awareness in Krishnamurti's, and self-remembering in Gurdijeff's teachings. Washburn highlights that both practices have been encouraged in Tibetan Buddhism and Zen Buddhism. Table 3.1 juxtaposes the two types.

Table 3.1: Comparing concentrative and receptive meditation.

	concentrative	receptive
	active	passive
	closed	open
	forced	voluntary
	focused	delocalised
	zoom in	zoom out
internal/external object	both	both
number of objects	single	multiple
filter	narrow	wide
length of meditation	unfixed	unfixed
information flow	sequential	non-sequential
Taoism	jang	jin

The further meditation transcends our attention, the more secrets of our subconscious processes can it reveal to our conscious processes. In receptive meditation, we can step back and look at our framing of reality, discover where it might be distorted and then use these discoveries to break out of inappropriate framing (e.g. undesired instinctive behaviours triggered by certain situations). With concentrative meditation, we train our attention to ignore irrelevant information and focus on what is salient for progress. Meditation can help our sense-making and the integration of insights into our everyday lives.

In the light of cognitive and neuroscientific studies (Banquet, 1973; Cahn and Polich, 2006; Lutz, Dunne and Davidson, 2007; Lee et al., 2018; Tarrant, 2020), meditation has also been defined more empirically. These new studies contribute to previous theoretical and qualitative research with quantitative measurements of biological rhythms (e.g. brainwaves monitored by BCI systems).

3.3.2 NeuroMeditation

Despite a growing interest in meditation over the last few decades, it is still a difficult practice for many people for various reasons 'ranging from a lack of time to general laziness' (Brandmeyer and Delorme, 2013). How NFT can support meditation is the key research focus at the NeuroMeditation Institute in Eugene Oregon (Fig. 3.14). Director Jeff Tarrant defines meditation as follows:

> A systematic mental training designed to challenge habits of attending, thinking, feeling, and perceiving (NeuroMeditation Institute, 2019)

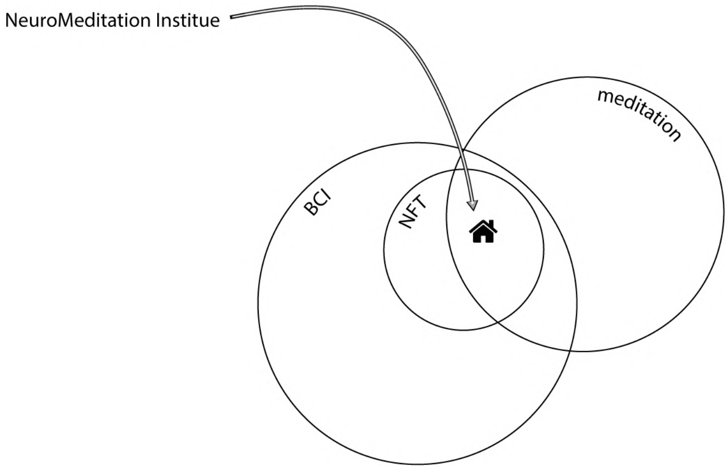

Figure 3.14: Venn diagram situating the NeuroMeditation Institute at the intersection of the domains of NFT and meditation.

NeuroMeditation is a type of NFT that can help novice and advanced meditators improve their meditation practices by providing immediate feedback on their internal states (Tarrant, 2017; 2020). NeuroMeditation combines the ancient wisdom of meditation with modern computer science. It provides a secular framework to begin and maintain the practice of meditation with neurofeedback protocols using standard qEEG or LORETA feature extractions. The five standard qEEG protocols are:

- focus protocol
- two mindfulness protocols: thoughtless awareness and thoughtful awareness
- open heart protocol
- quiet mind protocol [7]

The focus protocol proposes to improve focus, attention and executive functions to aid people with cognitive decline, memory problems and attention deficit disorders. It is based on how meditators shift and sustain attention using three different brain networks. In mind wandering the default mode network, when redirecting attention the salience network, and when maintaining attention on a specific object (e.g. breathing), it is the executive attention network that is most active (Hasenkamp et al., 2011). To be

[7] As my research has not used LORETA feature extraction, I have only outlined the standard qEEG protocols. More information on the LORETA protocols can be found in Tarrant's cited papers and brief video introductions to these protocols on the NeuroMeditation (1995) YouTube channel.

focused, the executive attention network needs to be engaged, and the default network mode needs to be quiet; therefore, as seen in Fig. 3.15, this protocol rewards

- increased gamma (35-45 Hz) on F4 and
- increased alpha1 at 8-10 Hz on Pz

Tarrant sometimes rewards increased gamma in the first part of the training session, and then, instead of increased gamma, he rewards increased beta in the second half of the session (NewMind Technologies, 2018). He also suggests experimenting with rewarding the decrease of faster brainwaves (beta or gamma) with an inhibitor on the default network mode, e.g. on Pz (NewMind Technologies, 2019). During a focus session, trainees intend to hold their attention on a single object, and when their mind wanders, they intend to bring attention back to the object. It is important to note that increased high-beta could indicate trying to focus too hard instead of actually being focused. Therefore, a qualitative questionnaire after the session is essential to provide clarification.

The institute distinguishes two types of mindfulness meditations and has designed two different protocols accordingly (NewMind Technologies, 2019): thoughtless awareness and thoughtful awareness. These protocols propose to help meditators distance their attention from thoughts and feelings while sustaining a calm awareness with open monitoring. They are often used to alleviate stress and anxiety. With these two protocols, trainees intend to pay attention to what is happening in the present moment while trying not to become attached to anything. The state of mind aimed for is an observer mode with a non-judgemental awareness of the present moment. With a thoughtless awareness protocol, trainees intend to allow whatever objects emerge in their awareness and pay attention to these objects while trying not to get attached to them. This protocol, as seen in Fig. 3.16, rewards

- increased theta on Fz and
- decreased gamma on Pz

With a thoughtful awareness protocol, trainees have slightly more control over their attention than with the previous mindfulness protocol. Similarly to thoughtless awareness, trainees also need to pay attention to objects emerging in their awareness without getting attached to them however, they are encouraged to guide their attention from object to object. This protocol is often used in connection with body scanning, progressive muscle relaxation and healing imagery. The protocol, as seen in Fig. 3.17, rewards

- increased gamma on C4 or T4 and
- increased gamma on Pz

The open heart protocol proposes to help improve trainees' moods by making them feel more empathetic and kind. It is often used to heal depression and improve relationships by building empathy. Trainees with this protocol first intend to activate positive emotional states associated with loving-kindness and compassion (Hutcherson, Seppala and Gross, 2008), gratitude (Kyeong et al., 2017) or forgiveness

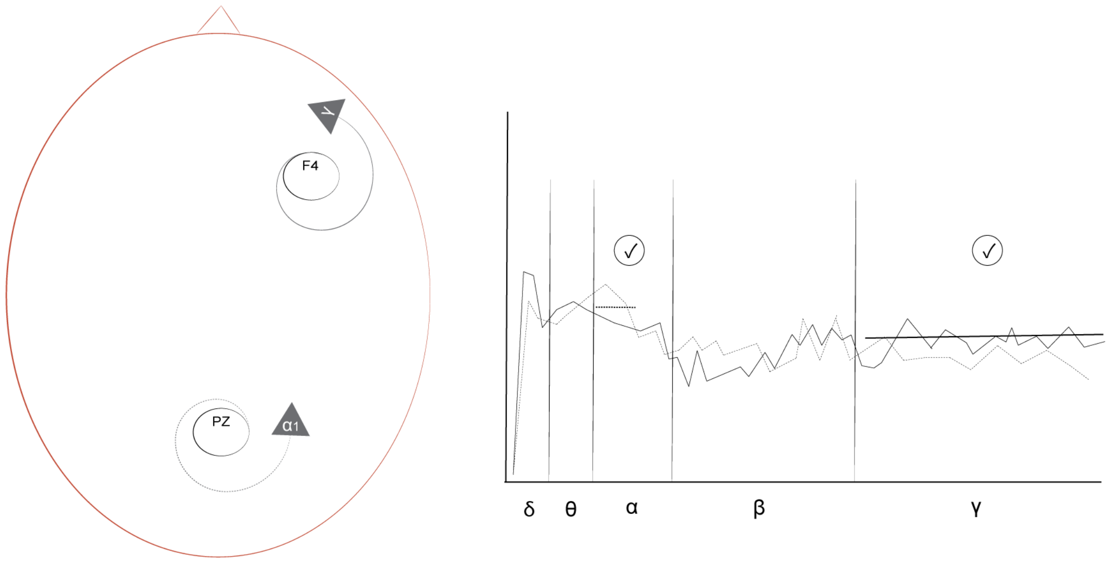

Figure 3.15: A focus protocol's electrode location (left) and a spectral plot (right) showing the application of two indicators, one applied on gamma on F4 and the other on low-alpha at Pz.

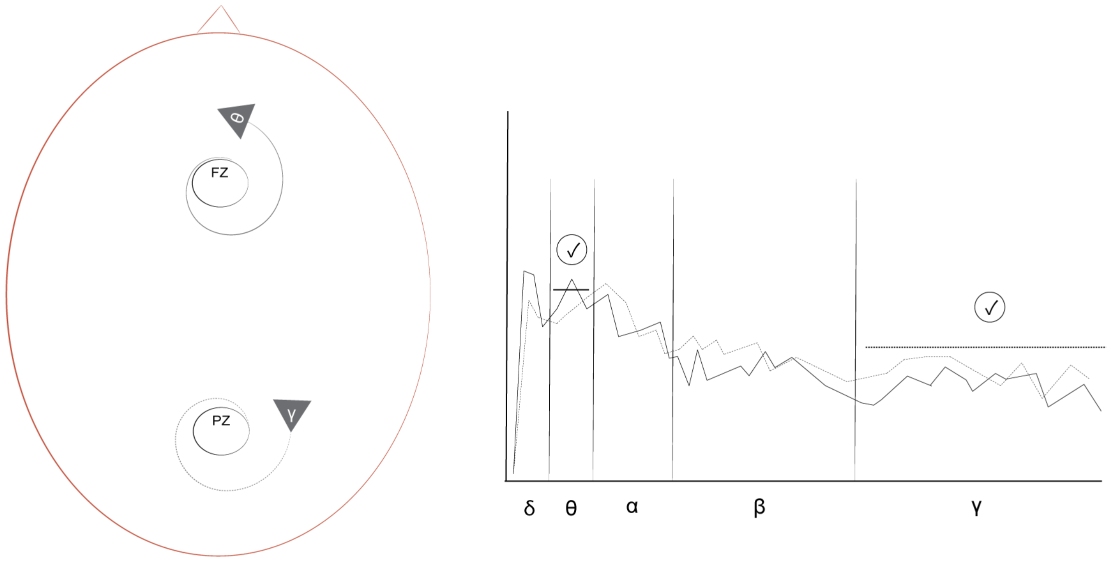

Figure 3.16: A thoughtless awareness protocol's electrode location (left) and a spectral plot (right) showing the application of one indicator on Fz and one inhibitor on Pz.

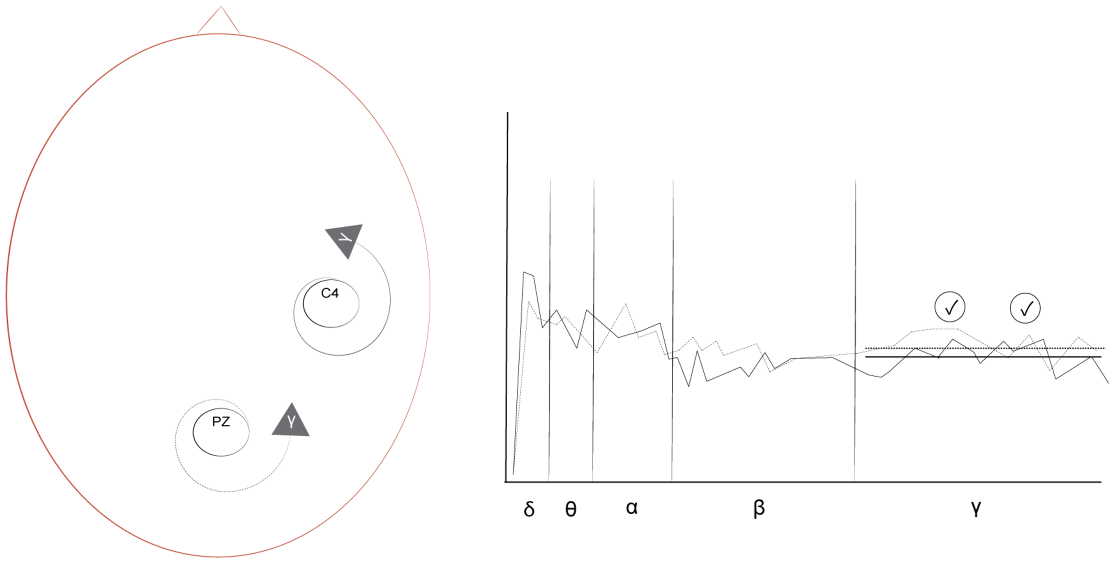

Figure 3.17: A thoughtful awareness protocol's electrode location (left) and spectral plot (right) showing the application of two gamma indicators.

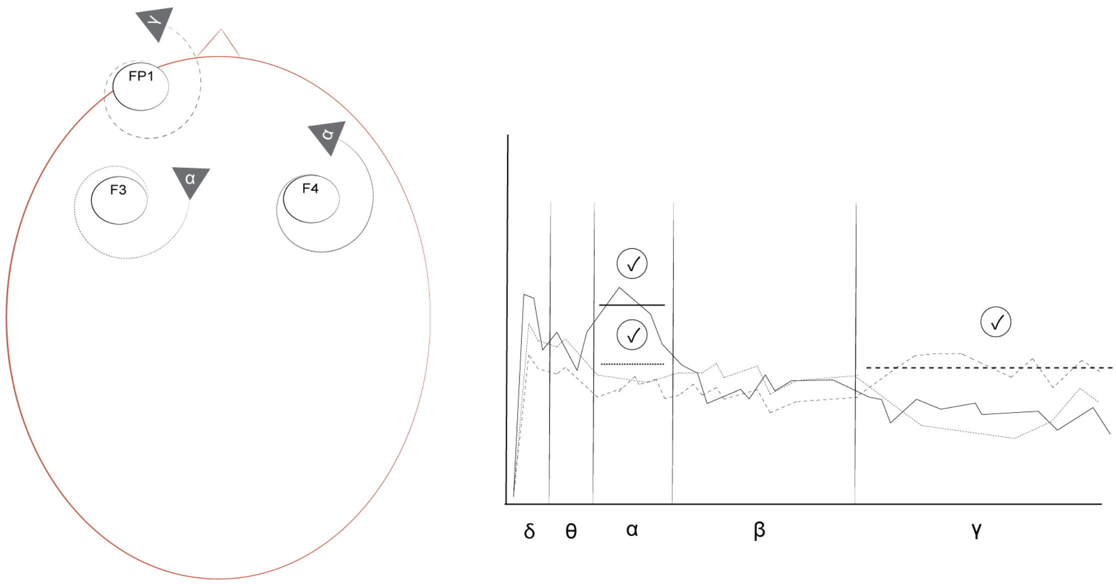

Figure 3.18: An open heart protocol's electrode location (left) and a spectral plot (right) show the application of one indicator on the right hemisphere (F4) and one inhibitor on the left hemisphere (F4), with the addition of another indicator on Fp1 rewarding increased gamma.

meditation practices (Menahem and Love, 2013) and then 'do something' with the positive emotional energy arising from these mental states. For instance, trainees can move this emotional energy around their bodies to target an unhealthy organ or 'send out' this positive energy with healing intentions to other people. The protocol is designed to train trainees' nervous systems to focus on the positive aspects of life. It is based on the asymmetry of frontal brainwave patterns linked to positive and negative emotional states. In a more positive emotional state, the left, in a more negative emotional state, the right hemisphere is more active (Sutton and Davidson, 1997). Therefore, the protocol, as seen in Fig. 3.18, rewards

- increased alpha (8-12 Hz) on F4 while
- decreased alpha (8-12 Hz) on F3 and
- increased low-beta (15-18 Hz) or gamma (35-50 Hz) on Fp1 or F3 or F7

The quiet mind protocol proposes to help minimise internal self-talk by experiencing peace and calmness. It is often used to address eating disorders, obsessive-compulsive and personality disorders and to facilitate transcendence. With the focus protocol, the intention is to hold attention on one thing, while with quiet mind to not hold attention an anything. A quiet mind training should start with similar brainwave patterns to those aimed for in a focus training (less rear and more frontal brain activity in the higher frequencies); however, after some time, the whole brain should become 'quieter'. A type of meditation that falls into this category is Transcendental Meditation (Tarrant, 2017, p.70). In a successful quiet mind session, the low-alpha (8-10 Hz) is the most active, while all other brain rhythms are subtle. This protocol, as seen in Fig. 3.19, rewards

- increased low-alpha at 8-12 Hz to start with, and later at a narrower 8-10 Hz on Pz and
- low-alpha coherence between Fp1 and Fp2 or between F1 and F2

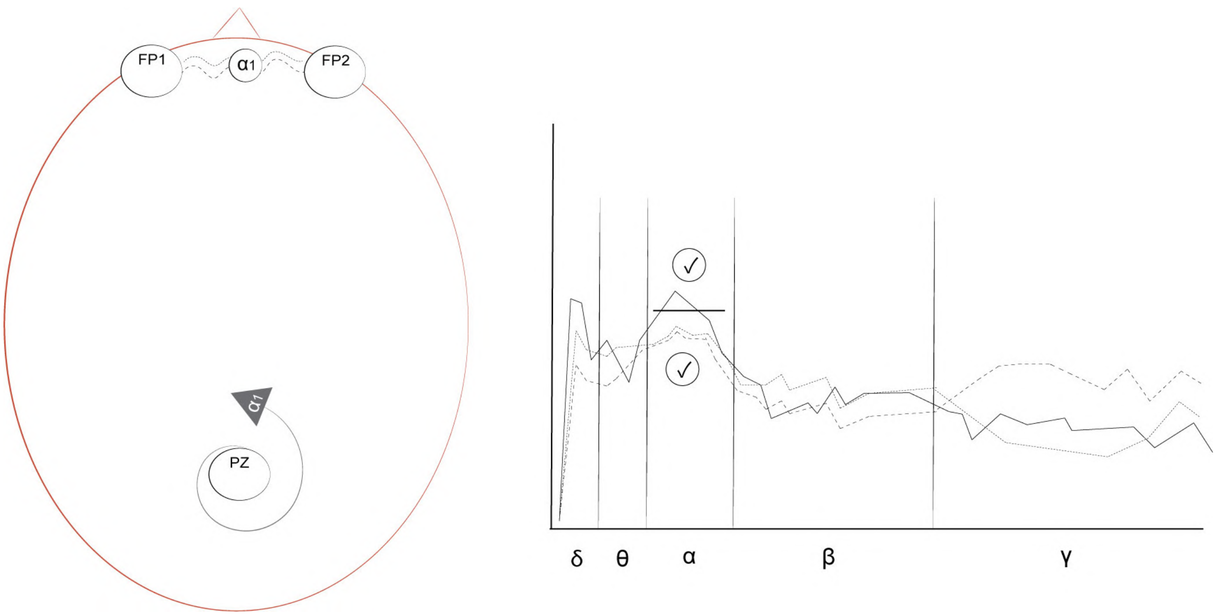

Figure 3.19: A quiet mind protocol's electrode location (left) and a spectral plot (right) showing the application of one indicator rewarding increase of low-alpha on Pz and another indicator rewarding low-alpha coherence between FP1 and FP2.

The focus protocol clearly trains concentrative, while the two mindfulness protocols receptive meditation. As we need to focus on a specific feeling or emotion in the open heart training, I believe we could consider it training concentrative meditation. Quiet mind seems to benefit from initially using mental techniques that zoom in (concentrate) and then methods that zoom out (receive) until the meditator reaches a breakthrough

3.4 Auditory Rhythmic Entrainment (ARE)

3.4.1 Introduction to entrainment

Research suggests a relationship between the tempo of music and the physiological changes that take place in the listener (Neher, 1962; Huang and Charyton, 2008; Jovanov and Maxfield, 2011). This relationship is thought to be based on the principles of synchronisation, often referred to as entrainment, frequency entrainment, frequency following response, locking or phase-locking (Pikovsky et al., 2001). When it relates to sound and music, entrainment is also described as sonic entrainment (Goldman, 2000), rhythmic entrainment (Strong, 1998; Trost, Labbé and Grandjean, 2017), sonic driving (Wright, 1989; Brilla and Hatcher, 2000; Harner, 2013), auditory driving (Turow, 2005; Fachner, 2011; Will and Turow, 2012) and sometimes as auditory beat stimulation (Chaieb and Fell, 2017). The essence of synchronisation, first written about by Christiaan Huygens in 1665 (Pikovsky et al., 2001), is the adjustment of two or more rhythms of oscillating objects due to their weak interaction. Weak interaction means that

> ... [the synchronisation] is not qualitatively changing the behaviour of either one of the interacting systems and should not deprive the systems of their individuality... (Pikovsky et al., 2001, p.17)

For example, stopping one system should not stop the other system.

Synchronisation can be in-phase, anti-phase, phase-shifted or complete. It is not to be confused with resonance, where one of the systems in the interaction has no rhythm of its own. In synchronisation, all systems have their individual rhythms. The synchronisation of rhythms is a universal phenomenon. It can be perceived in other non-music-related disciplines, such as biological sciences (McClintock et al., 1971; Bramble and Carrier, 1983; Niizeki, Kawahara and Miyamoto, 1993) and social sciences (Blasius, Huppert and Stone, 1999; Néda et al., 2000). A common method of synchronisation is pacing and mirroring in nonverbal communication, often used to establish rapport in business (Fatt, 1998) and parenting (Bryson and Siegel, 2012). A general principle of music therapy also links to synchronisation:

> If music is to be used to reach and change a person, it should begin with matching the medium to the individual's current condition. (Donald and Pinson, 2012, p.19)

> [The iso-principle is] a technique by which music is matched with the mood of a client, then gradually altered to affect the desired mood state. (Davis, Gfeller and Thaut, 2008)

To help induce and maintain meditative states, I reviewed two methods of auditory entrainment:

1. Binaural beats, in which a monotonous rhythm is a subjective percept processed in the brain's medial superior olivary nuclei before being transmitted to the CNS.
2. Monaural beats, in which a repetitive rhythm is demodulated in the cochlea before being transmitted to the CNS (Chaieb and Fell, 2017).

A difference between binaural beats and monaural beats (e.g. repetitive drumming) is that binaural beats need to be listened to through headphones for the best effect and monaural beats do not. The headphones are required when listening to binaural beats due to the technology used to generate them. When listening to slightly different frequencies (e.g. 100 Hz through the left and 104 Hz through the right ear), the brain perceives the difference in frequencies (in this case, as a monotonous beat pulsating at 4 Hz). However, drumming with repetitive rhythms does not require headphones for entrainment, as its beats are within the human hearing range. Both methods are considered helpful for increasing the amplitude of a brainwave or, more specifically, the power of a specific EEG frequency band that aligns with the frequency selected for the entrainment. For example, binaural beats monotonously pulsating at 4 Hz should have the same synchronisation effect as repetitive drumming in which the beats hit the drum four times per second. When synchronisation is effective, the 4 Hz rhythm of either of these two methods is 'locked' to neurones in the brain firing at 4 Hz.[8]

3.4.2 Rhythmic Entrainment Intervention

Since ancient times, monaural entrainment with repetitive drumming has been used to help induce and maintain ASCs. A specific type of monaural entrainment is ARE, thoroughly explored in the works of Jeff Strong, the co-founder of Rhythmic Entrainment Intervention (REI) at the Strong Institute in Santa Fe, New Mexico (Fig. 3.20).

> Rhythmic Entrainment Intervention is an auditory brain stimulation program that uses musical rhythm to stimulate and re-pattern neurological function. A unique blend of modern advances in brain research and ancient rhythmic techniques, REI facilitates long-term behavioral and cognitive improvement in individuals with neurological disorders. (Strong Institute, 1994)

REI is a six-month-long programme aiming to alleviate the suffering of people with symptoms related to attention deficit disorders, behavioural issues (e.g. aggression), cognitive issues (e.g. memory loss), mood issues (e.g. depression), self-stimulatory behaviours (e.g. rocking), sensory processing issues (e.g. sensory defensive and sensory seeking behaviours), sleep problems (e.g. insomnia) and social challenges (e.g. inability to interact with others). The programme evolved from live stimulation through customised audio CDs to the current online platform. During live stimulation, the trainer adjusts the music in response to the changes seen in the patient in the same physical space and time. With CDs and the online programme, the

[8] Whether the amplitude of the selected frequency in the brain can increase by exposure to the stimuli through passive hearing or whether we can produce this increase only by actively (intentionally) listening to the stimuli is an important question I am still investigating. I am also interested in finding out how imaginative stimuli could affect brainwaves — for example, how we entrain our brainwaves by simply 'drumming' in our heads.

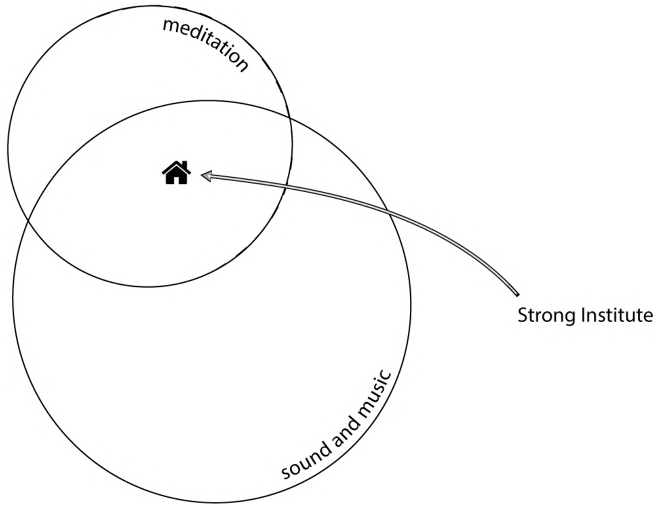

Figure 3.20: Venn diagram situating the Strong Institute at the intersection of the domains of meditation and sound and music.

trainer and trainee do not share the same space and time; the work is done remotely using feedback forms. The current online programme consists of a series of weekly updated audio files, each carefully customised to trainees' initial conditions and developments throughout the programme. The audio files are between 20 and 30 minutes long and are generally encouraged to be listened to passively as background music. These files contain solo drumming that pulsate around 8 beats per second (BPS), double the tempo heard in most traditional shamanic drumming. Listening to REI is proposed to help reduce trainees' symptoms by increasing alpha brainwaves associated with calm.

> In order to induce calm, with drumming, play rhythms at 8 beats per second that are variable enough to keep the brain engaged, but not so variable as to make the brain have to work too hard... (Strong, 2018a)

The REI was created in 2004. It is based on the ethnomusicological research of Jeff Strong, who has worked with percussionists from different traditions, including Haitian Vodou, since 1983. In REI, he synthesised his discoveries on how tempo and rhythm have been used in different traditions to alter listeners' states of mind. He says:

> You can affect consciousness, cognition, and behavior by employing only two specific rhythmic techniques. One consists of a repetitive pulse while the other employs complex rhythmic structures. (Strong, 2010)

Strong's secularised methods have been investigated in controlled settings (Strong, 1996b; 1996a; 2012a; 2012b; Oostra, 2012), more recently, involving OpenBCI (Strong, 2018b).

The REI method uses the principle of synchronisation. As with binaural and monaural beats, the drumming in REI also has a specific tempo to increase the amplitude of the trained brainwaves, but in addition to this, the complexity of its rhythm is also aligned with these brainwaves. In general, the faster the tempo, the more variation Strong suggests the rhythm needs to keep the brain engaged. For instance, when entraining slower brainwaves (delta, theta, low-alpha), the drumming can be repetitive with simpler rhythms. However, when entraining faster brainwaves (high-alpha, beta, gamma), the drumming should be less repetitive and use variations of more complex rhythms (e.g. with odd meters and random changes). Strong's ARE works to entrain brainwaves with the stimuli's tempo and rhythm:

> As I developed Rhythmic Entrainment Intervention (REI), my first step was to identify the core mechanisms of the traditional techniques. It turns out that these mechanisms are simple, powerful, and easily understood. First, human consciousness can be directly affected by an auditory stimulus. This is called 'auditory driving' (Goldman, 2000). Auditory driving states that a listener's brain wave activity will synchronise with the pulsation of an auditory rhythm (provided certain conditions are met). . . . The second core mechanism involved in traditional therapeutic rhythm techniques consists of using complex rhythms to activate the brain (Shatin, 1961; Scartelli, 1987; Parsons, 1996). Here complex auditory rhythms stimulate the Reticular Activating System (RAS), a part of the brain that controls sensory input (Scartelli, 1992). Applying rhythm - especially complex rhythm – to activate the brain is one level of the stimulation provided by REI. As we conducted research we discovered another dimension to the rhythms: one that appears to be more important than just complexity. It seems that each rhythm produces a different response. (Strong, 2010)

The customised audio files in REI are constructed from short audio samples capturing over 600 rhythmic patterns. In general, entrainment in the audio files starts with less complex rhythms and, throughout the programme, gradually moves towards more complex rhythms (Strong, 2016), as seen in Fig. 3.21.

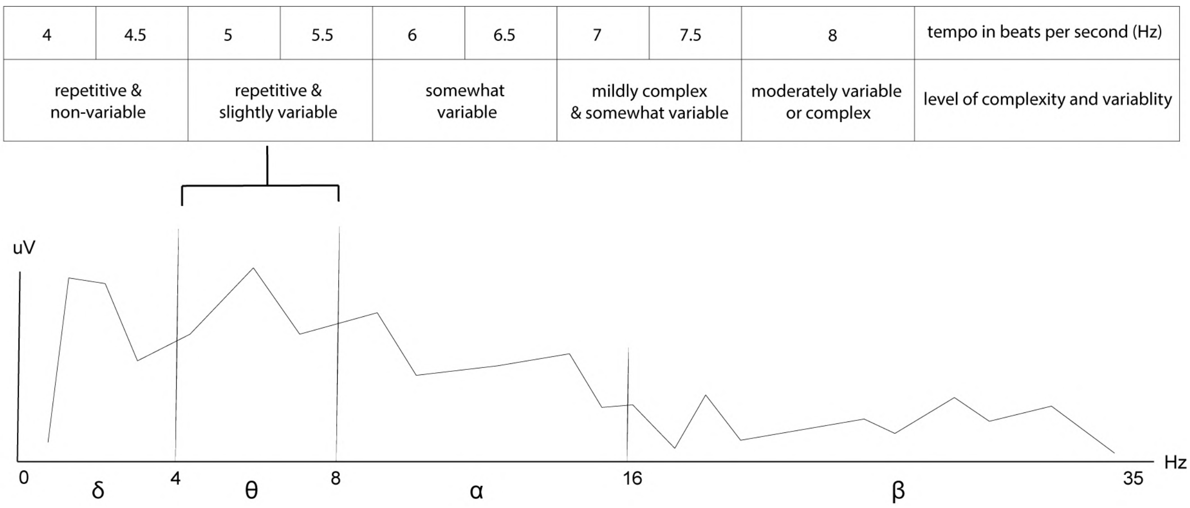

Figure 3.21: FFT plot aligning tempo and rhythmic complexity (top) with theta brainwaves (bottom) as in Strong's research.

The Strong Institute offers a similar programme called Brain Shift Radio (BSR) (2012), a dual-music-streaming platform where users can mix two types of music: solo or orchestrated (layered) drumming with ambient music (Fig. 3.22). Both types can be selected from various categories (e.g. brain-boost, calm, energy uplift, focus and meditation) and played simultaneously. Within each of these categories, sub-categories defined as 'energy levels' help further refine the intensity and uniqueness of the mix. The user controls the choice of audio samples and the volume crossfader between the two players and can even rate the created mix from one to five stars. The more stars a mix gets, the more likely the automatic playing mode will select this unique blend in the future. BSR was developed to fulfil an emerging need expressed by REI trainees; the need for music better suited for active listening (i.e. listening with a focus on the music instead of on another activity while the music is played in the background). Also, as some trainees found audio files with only drumming too hard to listen to, with the ambient sounds and customisability added, BSR expanded on REI and reached a wider audience. The main difference between the two programmes is that the audio file selection is trainer-controlled and contains primarily solo drumming in REI, while it is trainee-controlled and contains solo or orchestrated drumming mixed with ambient music in BSR. Trainees have more control over the entrainment with BSR however, they do not receive the personalised support offered with the six-month-long REI programme.

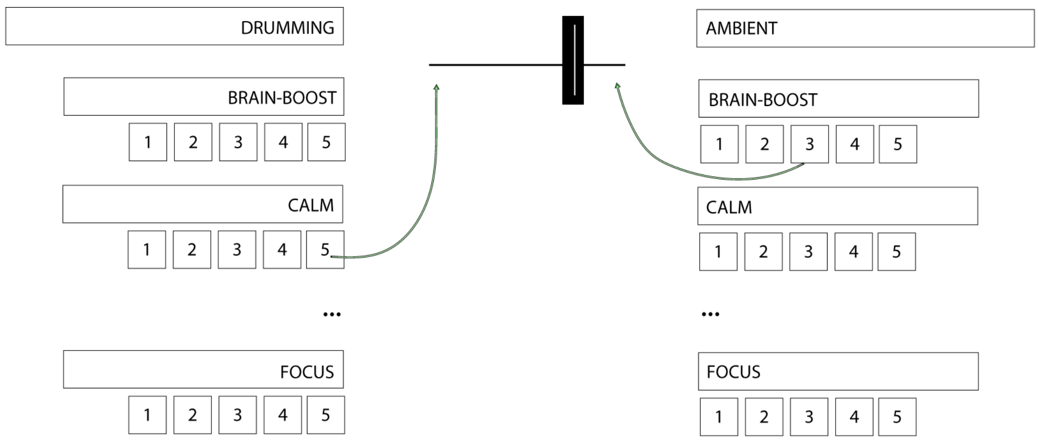

Figure 3.22: Brain Shift Radio's dual-music-streaming platform.

3.4.3 Shamanic journeying

Inspired by REI, I investigated how shamanic drumming has been claimed to help induce and maintain an ASC. Shamanic journeying is a specific type of guided meditation used in shamanic traditions in which practitioners aim to enter an ASC to communicate with 'spirits' and retrieve specific information from them (Fig. 3.23).

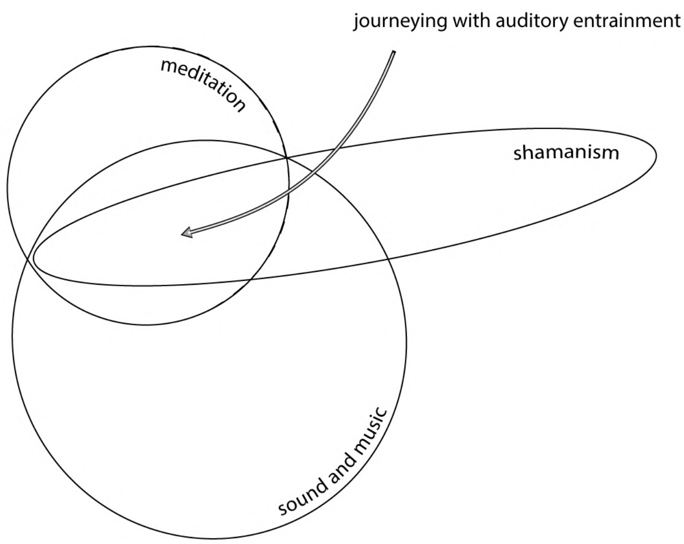

Figure 3.23: Venn diagram situating shamanic journeying with auditory entrainment at the intersection of the domains of meditation, sound and shamanism.

Shamanic journeying, often referred to as journeying or soul flight, aims to take participants on a trip to a non-ordinary reality (NOR), a hypnagogic state more recently defined as the SSC (Harner, 1980; Rock and Krippner, 2011; Huels et al., 2021). In the SSC, shamans or shamanic practitioners enter into

> controlled out-of-body experiences in which they experience themselves roaming at will through this or other worlds and meeting, battling, or befriending the spiritual inhabitants. (Walsh, 2001, pp.31–52)

Frecska, Hoppál and Luna (2016) define an SSC as an alternate source of environmental information that is opened through a 'nonlocal-intuitive' channel after a shift occurs in the journeyer's awareness through the use of psychedelics or contemplation. In Flor-Henry, Shapiro and Sombrun (2017), an SSC is

> a distinct sub-category of ASCs characterized by lucid but narrowed awareness of physical surroundings, expanded inner imagery, modified somatosensory processing, altered sense of self, and an experience of spiritual travel to obtain information necessary for solving a particular individual or social problem.

The methods with which the ASC is accessed in shamanic journeys are subject to cultural differences. For example, to create and maintain an SSC, some shamanic practices employ repetitive stimulation with psychedelic substances, and some do not (Fachner, 2006b; 2006a). As a result of his cross-cultural research, Michael Harner developed core shamanism to preserve shamanic knowledge and distil it for ordinary people to use for healing purposes. He states that 'most of the world's indigenous cultures did their work without the appreciable use of psychedelic substances' (Harner, 2013, p.40). With regard to differences in journeying, he writes as follows:

> . . . in some indigenous societies, there are shamans who do not journey at all, and others who journey only in the Middle World or, if they journey beyond the Middle Worlds, may not go to both the Upper and Lower Worlds. What they do share is disciplined interaction with spirits in nonordinary reality to help and heal others. (Harner, 2013, p.49)

NORs are most often experienced through visual imagery (Noll, 1983; Houran, Lange and Crist-Houran, 1997), but other sensory modalities can also occur (Walsh, 1995). Shamanic journeys are often accompanied by drumming to help induce an SSC, often by entraining theta brainwaves at 4 Hz in the EEG spectrum using drumming at a 4 BPS tempo (Jovanov and Maxfield, 2011). Participants in a journey often ask for clarity on a specific question. Shamanic practitioners believe that the clarification comes from the Spirit or spirits (Harner, 2013), while from a more scientific understanding, it is believed to come from the subconscious mind (Jung, 1960). It is also important to highlight that, although two shamanic practitioners can share a tradition (a belief system), their maps of meaning linked to the actual environments and spirits experienced in their individual journeys can differ (Harner, 2013, p.71).

> These original techniques are some of the most pervasive therapeutic practices known to man, existing on every continent even among people who had no contact with one another. (Harner, 1980)

Depending on the specific tradition, the tempo and rhythmic complexity of drumming in shamanic journeying sometimes does and sometimes does not change. For example, while core shamanic practices (Harner, 1980; Hove et al., 2015) use repetitive rhythm with a steady 4 BPS tempo, some shamanic traditions vary the rhythm and tempo, as does Strong (1998) in his REI for instance. In *Drums of Vodou*, the authors not only highlight the importance of different rhythms for calling different spirits but also emphasise that among the different instruments used for calling them, it is the sound of the drums that spirits prefer the most:

> The spirits love music, ... each has his/her favourite beat. From their locations in the cosmos, spirits respond to a complex of invitational signals sent out to servants, but the drum might be the most compelling of these. (Wilcken, 1992, p.47)

Maas and Strubelt (2003), in their study on Iboga healing ceremonies of central West Africa, also comment on the role of varied drumming patterns:

> The melodic motifs are repeated mostly after 2x12 or 4x12 elementary beats and undergo minimal melodic or rhythmic variations. Here the melodic rhythm frequently diverges slightly from the elementary beats, thus suspended between the two fundamental metrics. The repetitions lead to mental anticipations that are systematically frustrated by these minimal changes in order to 'keep you on the move', as the Mitsogho told us: they create the open-minded attention that is required.

The soundscapes generated with the BCMI-2 system attempt to employ both repetitive and varied stimuli (ARE), with additional sound textures that provide context for meaning and immersion (Chapter 5).

3.5 Serious Gaming and Spatial Audio

To learn about how to help induce and maintain ASCs, I briefly reviewed the literature related to serious gaming and spatial audio.

3.5.1 Serious gaming

Like meditation, games can also help one learn skills transferable to the real world (Ritterfeld, Cody and Vorderer, 2009). Games have rules and goals and are designed to facilitate immersion through sensory, imaginative and challenge-based strategies (Mäyrä and Ermi, 2011). Serious gaming is a type of gaming that has educational instead of entertainment purposes. For instance, a serious game can help people learn about historical events or help them make behaviour changes in their lives. When making a serious game, the developer must first ask who the players are and what will motivate them to play. Knowing these will help the developer successfully market and develop a game through which players can learn new skills effectively (Godin, 2018). What motivates gamers to play is investigated through the uses and gratifications theory (Wu, Wang and Tsai, 2010; Sherry et al., 2012) and the self determination theory (Uysal and Yildirim, 2016). Both theories highlight the importance of players' needs for autonomy/control, competition/challenge and relatedness to their interests. In addition, the uses and gratifications theory notes that playing should also provide diversion (something different) and social interaction. A specific type of serious gaming is called persuasive gaming, in which the method to help change or reinforce specific attitudes is persuasion.

> [Persuasion is] a successful intentional effort at influencing another's mental state through communication in a circumstance in which the persuadee has some measure of freedom. (O'Keefe, 2015, p.5)

The theoretical framework for persuasive games by De la Hera Conde-Pumpido (2017) aims to help design games that balance players' preferences (e.g. old habits) with persuasive goals (e.g. new habits). Her framework proposes three types of persuasion strategies: exocentric, endocentric and game-mediated.

The goal of exocentric (game-centric) strategies is to change the attitude of players beyond the gaming session by (1) conveying messages with signs embedded within the game, (2) the system itself allowing players to interact with the signs of the game and (3) the context in which the persuasive games are played. She says these messages can be implemented by 'linguistic persuasion, sonic persuasion, visual persuasion, haptic persuasion, procedural persuasion, narrative persuasion and cinematic persuasion'.

Endocentric (player-centric) strategies aim to motivate players to play and keep playing the game. For these strategies to be effective, they need to 'consist of relational structural elements designed to connect with the players' personality traits and their life context'. She recommends these messages to be implemented by (1) arousing sensory experiences, (2) arousing emotions, (3) delivering intellectual challenges and (4) encouraging players to establish relationships with other players.

The goal of game-mediated (context-centric) strategies is the same as that of the exocentric strategies; however, they focus on 'designing a game session in which the context in which games are played is under control and specifically designed to favour persuasion'. Based on Hung (2007), to design this context, De la Hera Conde-Pumpido suggests to '(1) construct new rules and protocols on top of ones existing in the game, (2) guide and foster offline conversations among players, and (3) design sessions that take advantage of the locally constructed and contingent factors of the context.' [9]

3.5.2 Spatial audio

> Spatial audio denotes the attempt to capture the salient parts of a sound field and reproduce it in some form at other, possible distant places (and times), such that a human listener perceives the spatial characteristics of the original sound scene to a large extent during reproduction. (Herre et al., 2015)

Spatial audio can (re)produce more immersive experiences than one-dimensional mono or stereo can offer — it can create 2D and 3D soundfields. Content creators who use these higher dimensions can create more realistic and immersive environments in which they can embed their stories. Apart from spatial audio's most common use in the film industry, gaming (Grimshaw, Lindley and Nacke, 2008), virtual realities (Çamcı and Hamilton, 2020) and electro-acoustic music (Bates, 2009), it has also been used to support inclusivity for visually impaired people (Heuten, Wichmann and Boll, 2006; Lopez, Kearney and Hofstädter, 2018) and for understanding data through listening when scientifically validating brain activity (Papachristodoulou, Betella and Verschure, 2014; Schmele and Gómez, 2014).[10]

[9] How I implemented some of De la Hera Conde-Pumpido's recommendations in my BCMI-1 system is discussed in Chapter 4 and that I consider implementing some of these recommendations in the BCMI-2 system is added to my new goals in Chapter 6.

[10] How I implemented spatial audio to help my audience become immersed in a soundscape generated by BCMI-2 is discussed in Section 5.5.

3.6 Brain-Computer Music Interfacing (BCMI)

3.6.1 Brain art

As outlined earlier, BCI systems are used in biomedical and non-biomedical, clinical and non-clinical settings, where the clinical applications focus on helping unhealthy people and the non-clinical applications on helping or entertaining healthy people (Mridha et al., 2021). Due to their technical nature, all BCI applications involve advanced scientific methodology, yet the methodology's level of rigour and the degree to which artistic methodology is integrated often depends on the purpose of the application (and the developer's skill) and not on whether the application is used in clinical/non-clinical or biomedical/non-biomedical settings. For instance, as evidenced in art therapy practices, art, including dancing, painting, and music, can be used in clinical and non-clinical settings (Landgarten, 2013; Fish, 2019). Also, while visualisation or sonification of brain data in surgical monitoring must focus on accuracy and timeliness with little room for creative (artistic) expression, recreational settings can turn this around. Novello (2012) states: 'Contrary to science, art can better accept instability and turn it into an interesting parameter'. BCI applications used for artistic purposes fall under the umbrella term 'brain art' (Nijholt, 2019), also referred to as 'artistic brain-computer interfacing' (Wadeson, Nijholt and Nam, 2015). Recent reviews of brain art with examples can be found in Nijholt (2019) and Gruber (2020).

3.6.2 BCMI systems

BCI systems mapping brain activity to parameters of sound or music are recently referred to as brain-computer music interfaces, a term originating from the Interdisciplinary Centre for Computer Music Research (ICCMR) at the University of Plymouth (Miranda and Castet, 2014). A BCMI system allows sound to be both the input for and the output of the brain, i.e. users can hear how their brain activity changes the sounds they are listening to (Fig. 3.24).

Eaton and Miranda (2014b) distinguish between the following three types of BCMI systems:

1. In a computer-oriented system, the user adapts to the functions of the computer. The computer model stays fixed, and the system's success relies on the ability of a user to learn how to perform control over musical events.
2. A user-oriented system is programmed to understand the meaning of user input in an attempt to adapt to its behaviour to achieve control.
3. A mutually-oriented system combines aspects of both user and computer orientation, whereby the two elements adapt to each other.[11]

As BCI systems, BCMI systems can also be classified based on their usability. They can be biomedical when used with unhealthy people (e.g. to aid their communication in music therapy settings) or with

[11] These terms are interchangeable with those established terms for BCI types in Section 3.1. A computer-oriented system can also be called hard, active or explicit and is linked to conscious operant conditioning. In this system, the user's deliberate cognitive choices are mapped to musical features. A user-oriented system can also be called soft, passive or implicit and be linked to spontaneous operant conditioning. Here the BCI is used to monitor unconscious activities that are used to inform the musical features. A mutually-oriented system can also be called a hybrid, in which both active and passive controls are used together.

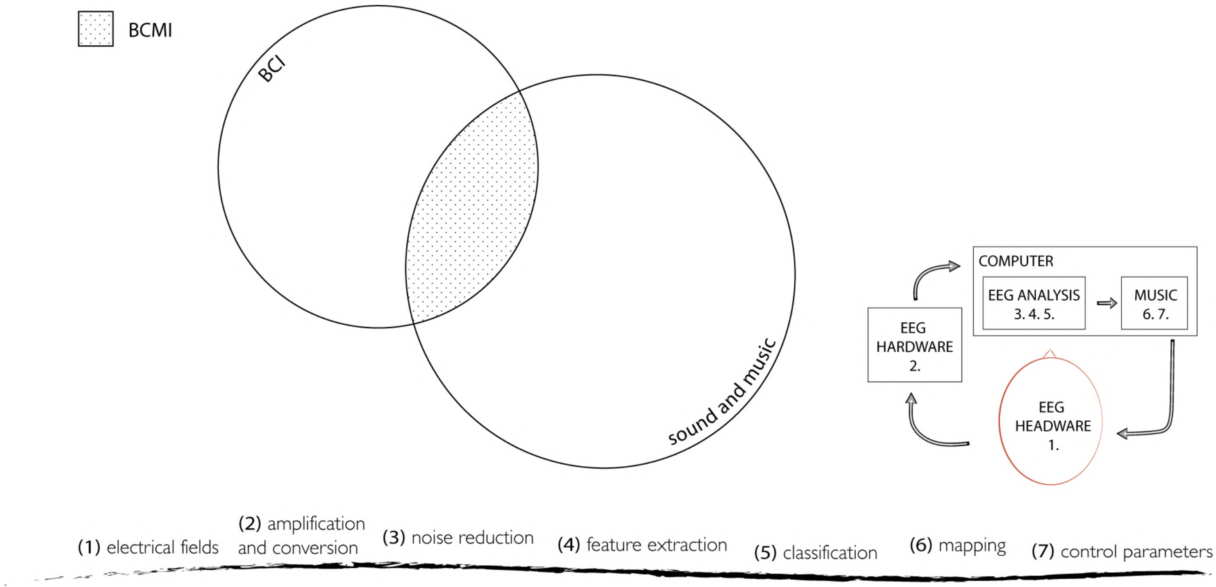

Figure 3.24: Venn diagram indicating the domain of BCMI being at the intersection of the BCI and sound and music domains (top left). All steps of a BCMI (bottom and right).

healthy people (e.g. to enhance a particular ability in NFT settings), and they can also be non-biomedical (e.g. when used in recreational settings with artistic expressions for composition and performance). BCMI systems can also be dependent or independent, synchronous or asynchronous, research- or consumer-grade.

3.6.3 A brief history of BCMI

BCMI grew out of artists performing with biofeedback systems in the 1960s. Since the advancement of technology towards the end of the last century, BCI systems became not only more accurate in recording and processing brain signals but also smaller, more affordable and often accompanied by software development packages - all helping their potentials to be further explored in artistic performances, in academic research and more recently in domestic settings. The following paragraphs will briefly outline this history and highlight some important and inspiring works.

At the beginning of the last century, advances in HCI allowed artists to experiment with biofeedback using sensors (e.g. cardiac sensors to measure HRV, EMG to measure muscle tension, proximity sensors to measure distance and EEG to measure brain activity). The first reading and visualisation of EEG are attributed to the German psychiatrist Hans Berger (1929), whose goal was to find proof of telepathy.[12] This development was largely ignored until five years later, when Edgar Adrian and his research student Bryan Matthews verified the method and created the first EEG sonification, which they proposed to be a good tool for exploratory analysis of brain signals (Lutters and Koehler, 2016). They wrote about the experience as follows:

> In this particular experiment, Adrian investigated whether disappearance of the alpha rhythm, which

[12] The link between Berger's spiritual and scientific life and a detailed outline of how he developed methods to understand the mind-brain relationship can be found in Millett (2021).

> generally occurred upon opening the eyes, would still take place in the absence of visual stimuli. Hence, the subject (Adrian or Matthews) was placed in a dark room to see whether the eyes could be opened without terminating the alpha rhythm (which was indeed the case). However, deprived of sight, it was no longer possible to watch one's own EEG recordings; a problem that was overcome by sonification, allowing the subject to detect temporal EEG changes upon opening or closing the eyes in the dark. (Adrian and Matthews, 1934) [13]

This, and subsequent developments in brain science, inevitably drew 'artists with an experimental bent' to collaborate with scientists (Rosenboom, 1990).

> If we accept that the perception of an act as art is what makes it art, then the first instance of the use of brainwaves to generate music did not occur until 1965. (Brouse, 2007) [14]

The first artistic performance using real-time EEG is widely considered to be *Music for Solo Performer* (1965) by Alvin Lucier in which alpha brainwaves were mapped to transducers accentuating percussion instruments 'including large gongs, cymbals, tympani, metal trash cans, cardboard boxes, bass and snare drums...' (Lucier, 1976). Since its 40-minute long premier, encouraged and live-mixed on eight channels by John Cage at the Rose Art Museum of Brandeis University, the piece has been performed by many other artists modifying the length of the performance and the mapping (e.g. by using switches operating radios, televisions, lights, alarms and other audio-visual devices instead of transducers accentuating percussion) (Lucier, 1995). Besides Cage, another person linked to this performance was the physicist and amateur organist Edmond Dewan, who developed a 'brain-control system' in the early 1960s that could not only turn a lamp on and off with alpha brainwaves but also send Morse code by producing shorter or longer audio signals (Kahn, 2013, p.95).[15] It was Dewan who initially introduced Lucier to an EEG and encouraged its use for performance. A detailed account of how Cage and Dewan helped Lucier, along with the technical details of this piece can be found in the work of Kahn (2013).

Soon after Lucier's experiment, another American composer, Richard Teitelbaum, also started mapping biological signals to sound in a series of artistic performances titled *Spacecraft* (1967) as a part of the Rome-based live electronic music group Musica Elettronica Viva. In these improvised experiments, he mapped brainwaves acquired with EEG hardware, as well as heartbeats and breath with contact microphones to sound parameters on analogue Moog synthesisers. Teitelbaum carried on using EEG in other musical performances (e.g. in 1968 in *Organ Music* and *In Tune*) (Teitelbaum, 1976). As in Lucier's work, Teitelbaum's arrangements also involved an assistant fine-tuning the mapping between brain and

[13] This paper was also the first one to describe the frequency following response of the EEG, the basis for entrainment as discussed previously in Section 3.4.

[14] Prior to Lucier's well-known *Music for Solo Performer* (1965), I found three notable projects that mapped EEG onto sound. One was the EEG spectrophone (Kamp, Kuiper and Leeuwen, 1958), which 'transformed the EEG frequency analysis into sound by assigning a specific tone to each frequency band, rising in pitch with increasing frequencies' (Lutters and Koehler, 2016). Second, the previously mentioned Joe Kamiya and his neurofeedback system using sound to help learn control alpha brainwaves (Kamiya, 2019). Third, Krzysztof Penderecki's *Polymorphia* (1962) was composed for a large string orchestra in which a section in the musical score maps amplitude fluctuation of pre-recorded brainwaves to pitch notations for traditional instruments. Krzysztof recorded these brainwaves on people listening to one of his earlier compositions dedicated to the 1945 Hiroshima bombing victims. Polymorphia's distressing sound would later be used in two famous films, the supernatural horror *The Exorcist* (1973) by William Friedkin and the psychological horror *The Shining* (1980) by Stanley Kubrick.

[15] Dewan demonstrates his system in a short video at https://youtu.be/tvo7w1BvF2g.

music as well as the overall sound mix during the performance. However, while Lucier had performed and others had assisted in creating an aesthetically pleasing composition, in Teitelbaum's work, it was the other way around. *In Tune* visualised EEG for the first time in performance. Since its premiere, it has been performed multiple times with different performers and different sound materials. In 'Improvisation, computers and the unconscious mind', Teitelbaum (2014) outlines his early biofeedback music and its connection to meditation.

Another important American composer pioneering the use of brainwaves in musical performances is David Rosenboom, whose first public 'participation-performances' with EEG alpha-monitoring and heartbeat monitoring technique using visuals and sound is called Ecology of the Skin (1970). How the 'performer-participants' interacted with his custom-made electronic circuit to generate immersive sonic and visual environments is described in Rosenboom (1972). His first composition with EEG, *Piano Etude I* (1971), links repetitive motor tasks to increased alpha brainwaves. In the recorded version of this composition, Rosenboom played fast repetitive patterns on the piano, while at the same time, the fluctuations of his averaged alpha brainwave amplitude were mapped to filters processing the sound of these piano patterns. The more alpha waves he produced, the more high frequencies were allowed in the overall mix from the processed piano sounds. The result is a 14-minute flow of hypnotic patterns. His second piece with EEG, *Portable Gold and Philosophers' Stones* (1972), provides instructions for up to four performers. Each performer's theta and alpha brainwaves, galvanic skin response and temperature were analysed and mapped to frequency dividers and filters controlled by Rosenboom on his custom electronics system. To extract more meaningful data, besides the previously used FFT in *Piano Etude I*, the new works also extracted the coherence time of brainwaves and mapped it to parameters of sounds. 'The result is a slowly unfolding web of filtered electronic tones over a tanpuraesque fundamental, possessing the unhurried, stately grandeur of an electronic raga' (Rosenboom, 2019). His third piece using one performer's EEG, *Chilean Drought* (1974), continued the use of fast repetitive piano patterns, with additional live or pre-recorded instruments (e.g. voices speaking or chanting, electronics and percussion). The system mapped the relative levels of a performer's theta, alpha and beta brainwaves onto the volumes of three different recorded versions of a text about the Great Drought of 1968–69 in Chile (Rosenboom, 1997).

Another work from this period arose from the collaboration between French musique concrète composer Pierre Henry and scientist Roger Lafosse. In a series of live improvisation performances, Henry acquired his and the audience's brainwaves with Lafosse's *Corticalart* BCI system and mapped it to parameters of synthesised sound (Henry, 1971). Neidich and Anglès (n.d.) on their artbrain.org blog comment on this work as follows:

> The raucous blat-sound is an unrelenting analog free-electronic skree noise. Modern art is highly invested in the dream of unmediated musical/artistic expression, yet Henry directly attempts to locate a pure music flowing from the composer's head that results in discordant sound rather than anything that can be immediately recognized as a 'sensible aesthetic' or a deliberate sonic interpretation of conscious thought. Instead it is the uncontrolled and discordant epiphenomena of precognitive neuromodulated chemical activity. As a musician, Henry's head is covered in electrodes to capture

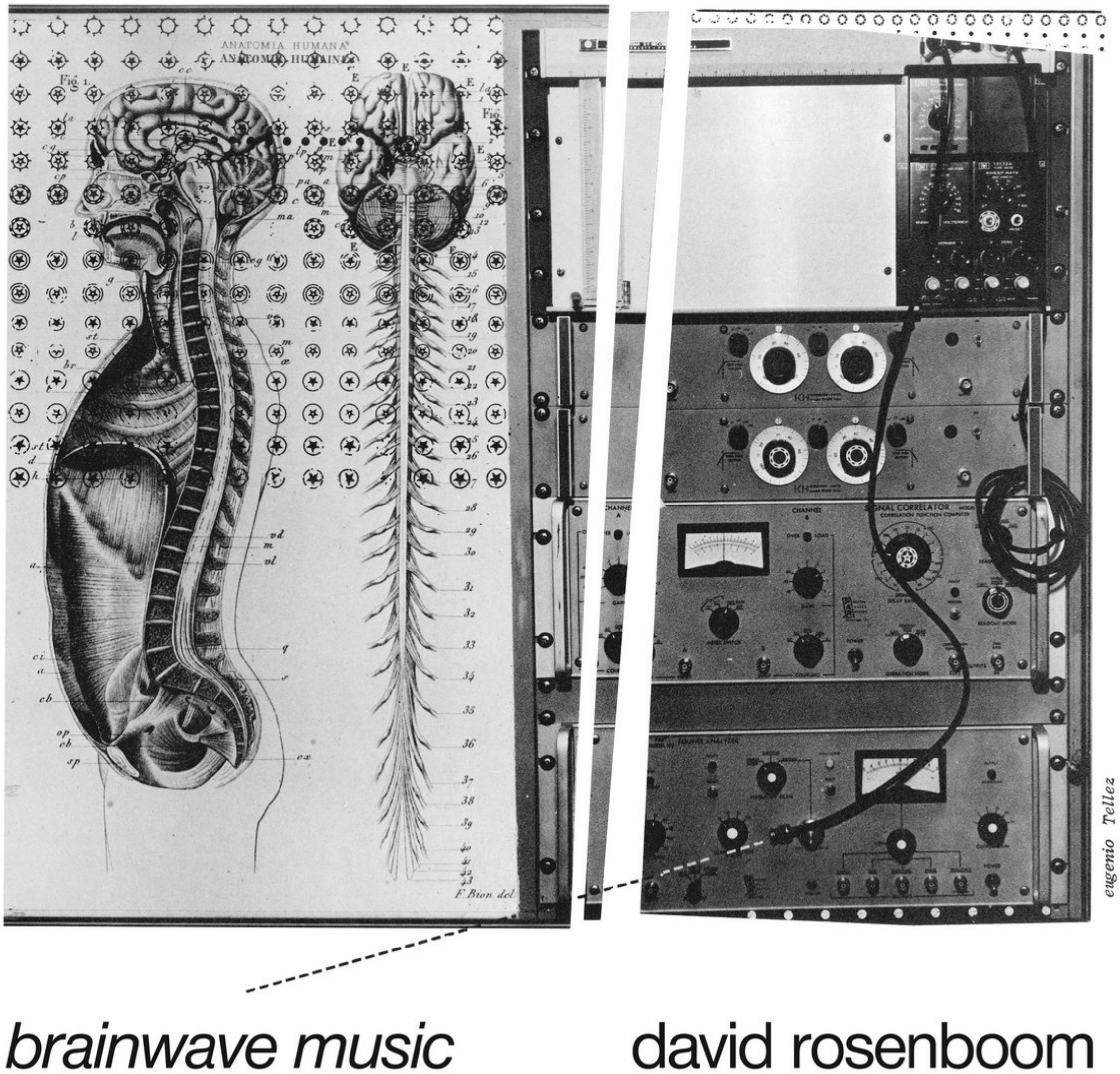

Figure 3.25: Cover art of David Rosenboom's *Brainwave Music*. This release is a collection of Rosenboom's compositions with EEG and other biofeedback hardware. Image courtesy of Black Truffle record label.

> alpha waves of relaxation and inattention, beta waves of alertness and attention, and 'artifacts' created by eye movements.

The BCMI projects in this period usually mapped the amplitude of brainwaves to various sound control parameters. While doing so, these performances highlighted BCI's potential for new artistic, ability-enhancing and therapeutic applications. The connection between biofeedback and artistic explorations comes as no surprise, as many of the pioneers I have mentioned were part of the counterculture growing strong in the 1960s and 70s, where followers commonly explored the use of meditation for raising individual and collective consciousness (Novello, 2012, p.16; Kahn, 2013, pp.90–91). Other notable works mentioned by Brouse (2007), Forcucci (2018) and Ortiz (2012) in their overviews of this period include the system designed by Manford Eaton (1973) intended to be used for 'bio-music', the artistic works of Stelarc, the Wellenfeld quartet, the Montréal group SONDE in Toronto, the Peabody Electronic Music Consort in Baltimore and the multimedia artist Erkki Kurenniemi in Finland. In addition, an excellent collection of essays reflecting on other early experiments can be found in *Biofeedback and the Arts - Results of Early Experiments* edited by Rosenboom (1976).

In 1973, UCLA-based computer scientist Jaques Vidal published his paper 'Toward Direct Brain-Computer Communication', describing the use of ERPs for conscious control. The first BCMI system using this feature was developed by Rosenboom for his *On Being Invisible* (1976-1979) project. Besides his earlier used touch-sensors, microphones and raw and spectral information of EEGs, this project also mapped ERPs to synthesised sound, providing an additional possibility to control sound parameters. The piece 'deals with the evolution of a system, of which the person [the brainwave performer] is a part, that goes through its own tendencies toward and away from order' (Polansky and Rosenboom, 1983). In general, the brainwave performer shapes the soundscape by consciously or unconsciously shifting between listening more actively or passively to specific parts of the soundscape. Rosenboom calls the soundscape an 'attention dependent sonic environment' produced by a self–organising, dynamical system (1997, p.74). The result is an over 40-minute-long synthetic piece gradually evolving from calm and meditative to sharp and alert. For Rosenboom, this piece 'contains the richest aesthetic, symbolic and metaphorical content arising from the import that biofeedback systems had on [his] work as a composer' (2022). Miranda (2014) sums up how the BCMI research community refers to this piece:

> This was an important step for BCMI research as Rosenboom pushed the practice beyond the direct sonification of EEG signals, towards the notion of digging for potentially useful information in the EEG to make music with.

After the initial attention that 'brainmusic' received in the 1960s and 70s, during the 1980s and 90s, artists seem to have lost interest in further experiments, which Brouse (2007) links to 'lack of funding and of sufficiently powerful computers' while Novello (2012) ponders whether artists were discomforted by the complexities involved in BCI signal processing. However, further technical advancements led to more affordable hardware, more advanced DSP, more user-friendly options for customisation, further research into sonification and the internet allowing swift discourse between collaborators (Ortiz, 2012). All of which contributed to the renewed interest in BCMI from artists and scientists.

While Rosenboom has continuously refined his On Being Invisible system over the years (for exammple to predict ERPs and detect shifts in performers' attention more precisely), the major components of it have remained untouched. However, after several years of hibernation, it formed the basis of a new system to perform the multimedia chamber opera *On Being Invisible II - Hypatia Speaks to Jefferson in a Dream* (1994). Rosenboom writes about this new system as follows:

> A powerful, widely–used software tool which I co–authored, known as HMSL, (Hierarchical Music Specification Language), is used to manipulate formal musical elements referred to as morphologies, or morphs, for short. ERPs' from the performer–subjects are then analyzed to determine if the computer's predictions correspond to signals from the brain that should accompany important, attention–securing events. If they do not, the music generating algorithms are allowed to mutate into new forms and new predictions are tested. If the predictions are confirmed, the kinds of events reliably associated with these confirmed predictions gain prominence in the musical fabric. (2022)

A few years later, he revisited BCMI with three new projects. For *Ringing Minds* (2014), he developed a new system with cognitive scientists Tim Mullen and Alexander Khalil that controls sound and visuals with the inter-brain synchronisation of four performers' (e.g. averaged simultaneous ERPs). In addition to the EEG sonification using electronic sound resonators, two performers also respond to the changes in the soundscape, one with a 'stone-xylophone' and the other with an electric violin (Mullen et al., 2015). *The Experiment* (2015) maps classified EEG from four audience members to a bank of pre-recorded audio samples in real time. The classification uses 'significant, coincident shifts in brainwave frequencies coming from all audience members simultaneously' (Rosenboom and Young, 2015), representing shifts between specific states of mind, e.g. agitation, alertness or meditative focus. When recognised by the system, these shifts trigger audio files containing soprano singing with relevant lyrics and emotional tones. The piece starts with a male actor explaining the goal and the methods of 'the experiment' in baritone singing while a technician sets up the consumer-grade Muse EEG headbands on four audience members. This setup time also features electronic dance music (I assume to comfort the brainwave performers). Then, the actual experiment starts with the actor asking the brainwave performers to monitor their emotions while imagining themselves as children alone in a dark room: 'Are you tired, are you afraid, are you happy, or are you helpless?' Next, the interface detects the four performers' affected states and plays audio files with matching emotional content. With support from the Swartz Center for Computational Neuroscience, his *Portable Gold and Philosophers Stones* (1972) was reconstructed as a 35-minute-long performance with the subtitle *Deviant Resonances* (2015). The performance had two brainwave performers and a third performer using machines and traditional instruments. The composition's narrative is based on the two brainwave performers interacting with sounds by actively listening to them. These sounds are either generated algorithmically by the computer system or by the third performer, Rosenboom himself.[16]

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[16] Rosenboom (2022) provides more information about these three projects, including technical details. More information can also be found at https://davidrosenboom.com/. Rosenboom introducing and then performing *Ringing Minds* with his team at the Whitney Museum of American Art can be seen at https://vimeo.com/245622585. We can find the audio recordings of the other two pieces on his album *Deviant Resonances*, published by Ravello Records in 2019 at https://www.ravellorecords.com/catalog/rr8009/.

Two other inspiring BCMI projects used in artistic performance settings during the last 10 years are as follows. *Fragmentation* (2012) by Alberto Novello is an artistic performance in which a system using Emotiv hardware and SuperCollider software was trained to recognise affected states in the EEG using correlation methods (Fig. 3.26). The performer uses these affected states consciously, in a non-synchronous way, to control sound parameters. 'The recognition of a specific pattern triggers pre-defined synthesis algorithms that have inbuilt stochastic variation to keep the audience interested' (Novello, 2012). Luciana Haill's *The Phrontesterion* (2014-17) is a series of installations in which visitors to the exhibition meditate in a dentist's chair while a Dreamachine (originally designed by Ian Sommerville in the 1960s) attempts to increase their alpha and theta brainwaves with a stroboscope flickering at the relevant frequencies (Fig. 3.27). During this entrainment, Haill's IBVA system rewards increased alpha and theta brainwaves, via MIDI, by increasing the volume of an audio sample that loops the phrase 'I am that I am.' This sample is embedded in a multi-layered soundscape, including audio recordings of reactions from previous visitors, field recordings and quotes from the *Red Book* (Jung et al., 2009). Amongst other venues, the installation was exhibited at The Royal Academy and The Kinetic Art Fair in London, The Transmission Symposium in Bournemouth and the KIBLA Multimedia Centre in Slovenia.

Figure 3.26: Photo of *Fragmentation* (2012) with the performer. Image courtesy of Novello.

The academic environment probably most widely recognised for BCMI research is the aforementioned ICCMR, run by Brazilian composer Eduardo Miranda. Research at the centre covers musicology, composition, artificial intelligence (AI), quantum computing, neuroscience and the development of biomedical applications. In regard to BCMI, Miranda and his team's publications have focused on

Figure 3.27: Photo of *The Phrontesterion* (2017) with user and artist. Image courtesy of Haill.

addressing the possibilities of using BCMI systems for musical performance in biomedical settings to aid the expression of mentally or physically impaired people and in recreational settings with healthy users making electronic music. One of their first computer-oriented systems, the BCMI Piano, acquires EEG signals from two or more channels, extracts the most prominent brainwave with FFT and the complexity of these signals with a Hjorth analysis and then maps these two features to parameters of an AI generating music in different styles, tempos and complexity. This music can have 'more Schumann-like elements when the spectrum of the subject's EEG contains salient low-frequency components and more modern or jazzy elements when the spectrum of the EEG contains salient high-frequency components' (Miranda and Boskamp, 2005). One of their other systems, the 'Combined EEG System' extracts frontal hemispheric asymmetry, an indicator of arousal and valence of emotions, and maps this feature to an affective-based algorithmic composition's key, pitch and tempo to help people deal with expressing emotions through verbal communication. An exciting part of this system is that each piece generated is based on a simple musical phrase supplied by the user at the start of the process (e.g. a phrase with musical notes such as 'ABA', 'ABCD' or 'AABB') (Kirke and Miranda, 2011). A few years later, Miranda and his colleagues developed systems using steady-state visual evoked potentials (SSVEPs). These systems flash separate visual targets on a screen using unique frequencies, which, when gazed at by a user, are detected in their visual cortex's raw EEG. They used variations of these systems to help locked-in syndrome patients control music (Miranda et al., 2011; Eaton and Miranda, 2013a) and healthy people to perform electronic music (Eaton and Miranda, 2013b; 2014a). Other projects developed with Joel Eaton use emotion recognition to control sound, such as *Affective Jukebox* (Eaton, Williams and Miranda, 2014) and *The*

Space Between Us (Eaton, Jin and Miranda, 2014), as well as *A Stark Mind* (Eaton and Miranda, 2015), where besides SSVEP and emotion recognition, their system also used motor imagery to control sounds (Fig. 3.28). ICCMR researcher Andrew Brouse's works are also important contributions to the field (Brouse, 2001; 2007; Miranda and Brouse, 2005). More recent BCMI work from ICCMR includes Horrell (2020), Venkatesh, Braund and Miranda (2020) and Puetate (2022).

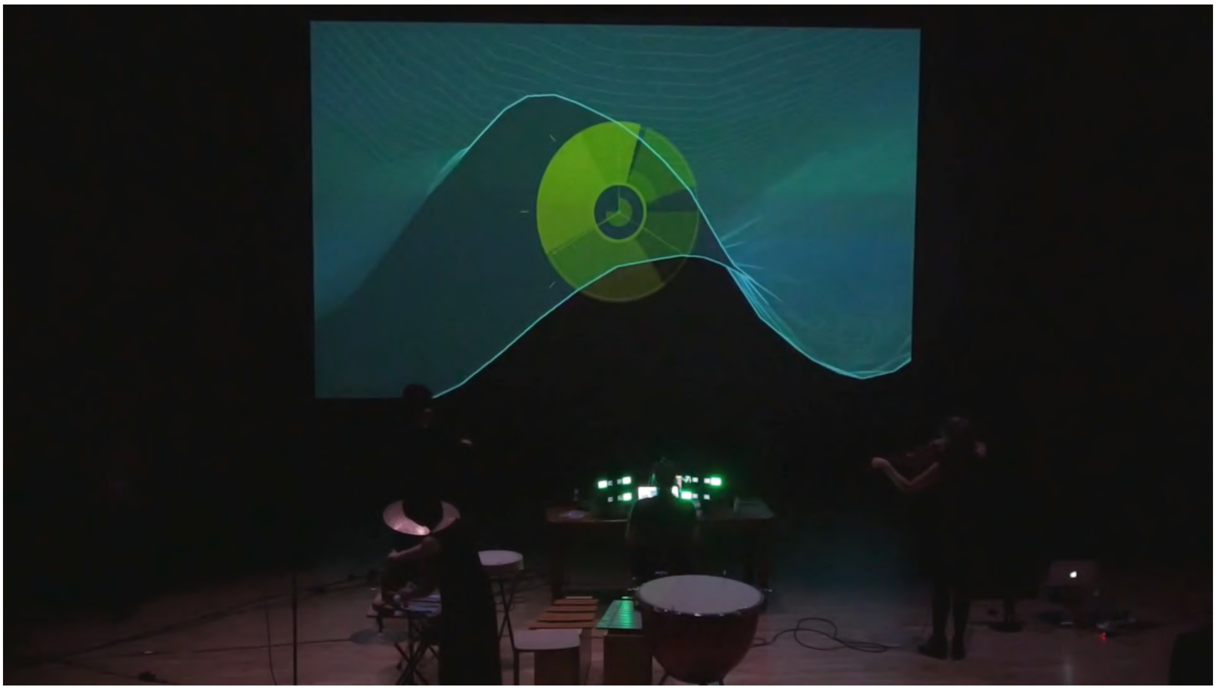

Figure 3.28: Photo of *A Stark Mind* (2015) performance at The House. Image courtesy of Eaton.

Other academic research advancing BCMI is linked to Mick Grierson and his collaborators, whose developments at Goldsmiths, University of London, have focused on providing active control over musical parameters with P300 ERPs using consumer-grade EEG hardware (Grierson and Kiefer, 2011; Grierson, Kiefer and Yee-King, 2011). Based on P300 spellers, their P300 Composer triggers synthetic notes (e.g. A1, A2, ... B1, B2) when relevant P300 ERPs are detected in users' EEG, first with research- (Grierson, 2008) and later with consumer-grade EEG amplifiers. A simplified version of this system is their P300 Scale Player, which by having fewer visual targets for the user to gaze at, provides faster interaction and therefore advantages for musical performances and video gaming. Another version of this system, as part of their EAVI BCI Toolkit, was used with ERPs controlling parameters of algorithmic composition in the audio-visual composition *Braindrop*. One method in this toolkit called Brainemin (Grierson, Kiefer and Yee-King, 2011) was used in the *Meditation* piece in Finn Peters' *Music of the Mind* project (Fig. 3.29). Brainemin mapped two classified signals from a NeuroSky BCI, the Attention and Meditation signals, to the pitch and vibrato of a synthetic sound generated in SuperCollider. In addition to this real-time method, Peters also used off-line sonification techniques in two other pieces on this release, *Sleep Music 1* and *Sleep Music 2*. Grierson and Kiefer (2014) outline these projects and provide guidelines for developers

Figure 3.29: Cover art of Finn Peters' *Music of the Mind* release. Image courtesy of Finn Peters and Finn Notman (visual artist).

who intend to use ERPs and repetitive serial visual presentation (RSVP) in BCMI systems.[17]

BCMI is also linked to Duncan Williams, who worked at the ICCMR, the University of York, and since 2019, at the University of Salford as a researcher of acoustics and audio engineering. Besides undertaking two of the most recent reviews in the field (Williams and Miranda, 2018; Williams, 2019), he co-developed BCMI systems with researchers at ICCMR (Eaton, Williams and Miranda, 2014; 2015) and more recently with BCI expert and computer scientist Ian Daly at the University of Essex. Based on previous work (Daly et al., 2015; 2016), their current system (Daly et al., 2020) identifies and modulates users' states of mind (their affective states) with algorithmically generated music. Their system's classification of affected states is based on the neurophysiological correlates of positive and negative emotions established by Stikic et al. (2014) and refined (personalised) in initial calibration sessions with users indicating their valence and arousal via a FEELTRACE interface (Fig. 3.30).

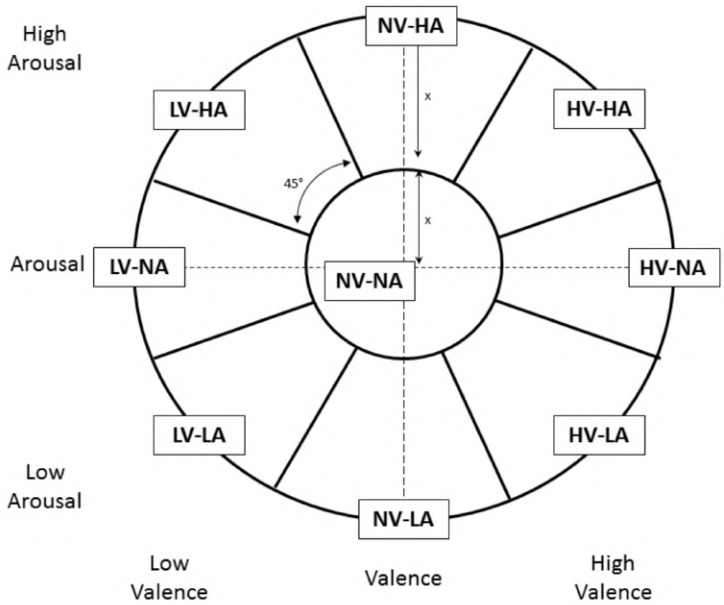

Figure 3.30: 'The segmentation of the FEELTRACE response space into discrete regions. Regions are labelled as low (L), neutral (N), and high (H) arousal (A), or valence (V)' (Daly et al., 2015). Image courtesy of Daly and Williams.

In addition to EEG, their system also monitors galvanic skin response (GSR), electrical activity in the heart (ECG), respiration, and blood oxygenation levels to help identify the affective states. The music responding to the changes is an affectively-driven algorithmic composition (AAC). In this system, the AAC is a monophonic piano piece generated based on known affective correlates of tempo, mode, pitch range, timbre, and amplitude envelope (Williams et al., 2014; 2015; 2017). While the system was able to modulate most users' affective states to be happier, calmer and less stressed, it could not excite (i.e. not

[17] In 2018, Professor Grierson moved from Goldsmiths to the University of the Arts London, where his work as Research Leader at Creative Computing Institute explores new methods to create audio-visual media with computer science.

increase users' levels of arousal). This, the researchers speculate, could be addressed in future work by generating polyphonic AAC with different types of instruments. Ehrlich et al. (2019) also developed a similar BCMI system.

Since technology has become more advanced and affordable in the last 20 years, numerous practitioners have explored the combination of biofeedback, meditation, sound and music for artistic, scientific and therapeutic purposes. To outline all of these works is outside the scope of this chapter. We can find more information on the history of BCMI, and its theoretical and practical methods in Nijholt (2019), Miranda and Castet (2014), Williams and Miranda (2018), Rosenboom (1976), Rosenboom (1997), Novello (2012) and Lutters and Koehler (2016). BCMI research has also been demonstrated at The International Conference on New Interfaces for Musical Expression (NIME), the eNTERFACE workshops and the events organised by the International Community for Auditory Display (ICAD).

3.6.4 Sonification, musification and control in BCMI

BCMI offers a wide range of creative expressions in the final mapping and control parameters steps that can help create aesthetically engaging experiences. These parameters can relate to sound or music (e.g. rhythm, pulse, tempo, duration, structure, volume, pitch, timbre, tonality, harmony, spatial location) and may be controlled on analogue or digital sequencers, samplers, sound oscillators, filters or timers. Mapping to these parameters, in general, can be simple or more complex, single or multi-layered, direct or indirect, linear or nonlinear, continuous or intermittent. Parameters can change at the composition's micro-level (e.g. when mapping the amplitude of a brainwave to the volume of a sound oscillator in a linear manner) and at its macro-level (e.g. when a generative algorithm creates sad music if a brainwave is weak and happy music when strong). The more recent user- and mutually-orientated systems also use machine-learning techniques for adaptive mapping. A similar phrase for 'mapping brain data to sound' is 'sonification of brain data'. Sonification, often referred to as audio display, audification or auralisation, is generally defined as the use of non-speech audio to convey information and, more precisely, as 'the transformation of data relations into perceived relations in an acoustic signal for the purposes of facilitating communication or interpretation' (Kramer et al., 2010).[18]

I conceptualise sonification on a spectrum where mapping techniques towards one end are simpler and more concrete, and towards the other end more complex and abstract. The former is sometimes called low-level sonification, and the latter, high-level (symbolic) sonification (Toffa and Mignotte, 2020). This spectrum can also be pictured as starting with transformations at the objective physical and mathematical level, then expanding into a more subjective physiological level and finally, breaking into the artistic level where creativity can flourish 'without limits' (Trček, 2018). While sonifications that aim for

[18] Both terms, 'mapping brain data to sound' and 'sonification of brain data' in the strictest sense are functionally analogous to the term 'neurofeedback with sound', i.e. when sound provides a form of feedback on neurological activity, although 'neurofeedback' conventionally implies that the feedback provided is in real time (on-line).

clearly understandable (more objective) interpretations are drawn to low-level, tight and linear mappings, sonifications that strive for more ambitious and aesthetic (more subjective) interpretations are drawn to high-level, multi-layered mappings. Novello (2012) helps clarify this difference:

> Several psychoacoustic facts show that translation of data into sound is useful when the data amount is too large or complex to be scrutinized by observation. It is easy to scroll through large amounts of data extremely fast, just by listening, because digitalized audio uses 44100 samples per second with CD quality. The sensitivity of a human ear for the detection of complex sound patterns and loops makes it a perfect tool for the detection of inner structures. The ability of the human auditory system to distinguish between several simultaneous voices or instruments even in a noisy environment (in contrast to the visual system's serial processing of multiple objects), provides a particularly good reason to use advanced sonification. ... in this field of research, however, the focal aspect is the reliability of parametric mapping and its recognizability. Aesthetics are a secondary priority.

Effective sonifications often map 'not just points but also the relationships among the points, from a source domain to a target domain' (Scaletti, 2018). However, as in functional translation in the field of linguistics (Nord, 2013), these points and their relationships should also be contextualised in the target domain. When a system sonifies data at the higher levels, mapping between the source and the target domains should not have to follow literal 'word by word', linear 'data by data' conversion; instead, it should be more agile and consider the new environment in which it needs to communicate meaning. Unfortunately, this liberty in artistic sonifications offers numerous temptations, often making the final output pleasing aesthetically but not engaging analytically. Neurofeedback trainer Tony Steffert comments on this temptation in regard to the sonification in his doctoral research:

> My sonification, for example, sounded horrible, but we aimed at faithfully representing the data. Some of the artistic sonifications lose their connection with the data, even though or maybe because of their beauty! (2022)

Sonifications can map single or multiple signals simultaneously to sound control parameters (e.g. to provide dynamics for nuanced sonic textures). While linear mapping of a single signal permits easier debugging of a computer program (Vickers and Alty, 2002), multidimensional mapping might be more useful when entertaining an audience of 'general' music listeners. The literature sometimes refers to high-level sonification as 'musical sonification' or 'sonification-based music genre' and includes several discussions on the similarities and differences between sonification and music (Dribus, 2004; Hermann, 2008; Schoon and Dombois, 2009; Vickers, 2016; Scaletti, 2018). The following definition from the BCMI literature provides a helpful distinction based not only on mapping but also on whether or not the output is performed artistically:

> The distinction between sonification and musification, both related forms of auditory display, is that in a musification, the data are not just auralized linearly, but instead, various constraints are created and applied in order to create a musical performance of the sonic data. This is an indistinct line and not easily delineated, but essentially the complexity and intent of the mapping involved determine whether the BCMI system is sonifying or musifying in its output. (Williams and Miranda, 2018)

Arslan et al. (2005) provide a similar distinction based on whether or not the output is intended for music production:

> Some research has already been done toward integrating BCI and sound synthesis with two very

> different approaches. The first approach aims to sonify data issued from physiological analysis by transforming them in sound (Berger, Lee and Yeo, 2001; Dribus, 2004; Potard and Schiemer, 2004). This process can be viewed as a translation of physiological signals into sound. The second approach aims to build a musical instrument (Miranda, Durrant and Anders, 2008). In this case, the musician tries to use his physiological signals to control intentionally the sound production.

Daly et al. (2016) also distinguish between sonification and musification:

> Sonification provides a method for passively monitoring affective states and translating them into audio output in a way that, it is suggested, may be useful for music therapy. In contrast, our aBCMI [affective BCMI] system first aims to classify a users' current affective state and then actively modulate that affective state via a music generator. Specifically, sonification generally provides a linear mapping between the neural signals (EEG or fMRI) and music, whereas our method is able to produce a wide range of different nonlinear streams of auditory cues in response to the affective states encoded within the neural signals.

In their real-time EEG sonification research review, Väljamäe et al. (2013) distinguish between four mapping approaches. (1) Audification, the most straightforward, oldest and largely obsolete method, pitch-shifts raw signals into the human hearing range. (2) Parameter mapping, the most popular method, maps parameters of a brain signal to parameters of a sound (e.g. alpha brainwave amplitude to the amplitude of a sound oscillator). (3) Model-based sonification generates sound with mathematical models. (4) The last, the generative music method, controls musical rules and structures with EEG data.

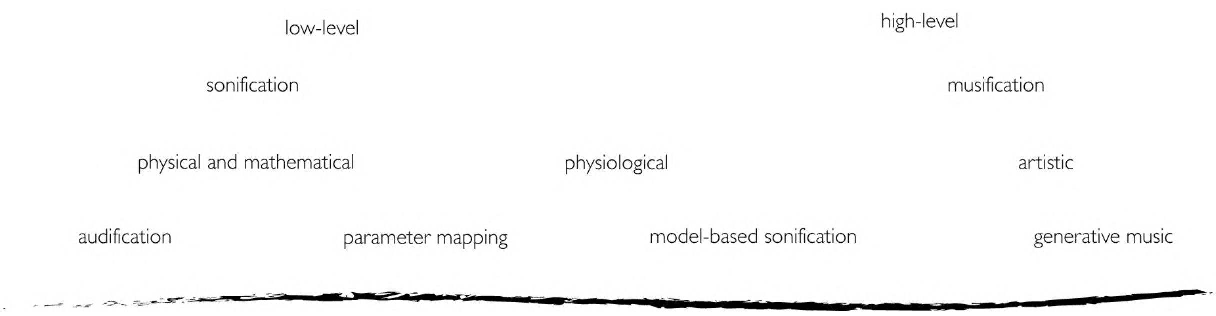

Figure 3.31: Sonification spectrum comparing the terminology used to differentiate techniques.

Based on these differentiations (see Fig. 3.31), we could define BCMI as BCI that musifies brain signals in real time for research and public performance purposes. However, before concluding this section, it is important to review how ICCMR researchers have distinguished between three methods for making music with EEG as well (Miranda et al., 2011; Eaton, 2016; Venkatesh, Braund and Miranda, 2020):

- sonification
- musification
- (BCI) control [19]

Their definitions of sonification and musification align with the above descriptions, except they note that sonification, 'while commonly used in non-musical, medical scenarios' (Eaton, 2016) as a method that

[19] Venkatesh, Braund and Miranda (2020) add audification as the fourth method, which aligns with the audification method of Väljamäe et al. (2013).

should be considered for musical purposes as well (Venkatesh, Braund and Miranda, 2020). 'Control', their third method, indicated (in some of their descriptions) 'active control' that provides users with 'direct cognitive real-time control of music' (Eaton, 2016), which then seemingly implies that when a system uses passive control, it is not BCMI:

> In addition to artistic use, sonification, and to a certain extent musification, can be useful for scientific applications; for instance, to monitor the EEG aurally. But they are of little value for BCMI proper because in those cases the user does not actively control the music; it is a passive affair. Conversely, in the control approach, the EEG signal is harnessed to control a musical system. Here the subject intentionally produces specific EEG patterns, which are detected by the system in order to control musical software. (Miranda et al., 2011)

> BCMI systems that sonify or musify raw EEG data without user control could be considered outside of the definition of BCI research. This is because BCI research is based on the premise that a BCI system allows for the active control of a system by the explicit thought of the command, and the results of the mental activity are fed back to the user in real-time. (Eaton, 2016)

However, elsewhere (Eaton and Miranda, 2015; Eaton, Williams and Miranda, 2015; Miranda and Eaton, 2018), it becomes clear that their definition of BCMI does indeed incorporate the use of passive control as well. Also, Williams, who developed passive BCMIs with ICCMR researchers and more recently with Daly, draws attention to the untapped potential of passive control:

> The potential to create systems for functional music (selection, performance, or even creation) in an unconscious manner (i.e., without the need for active management by the user) is enormous and perhaps the largest likely avenue for BCI music creation in terms of broad user base. (Williams, 2019)

It seems that while most researchers consider that BCMI can utilise both active and passive methods, their use of the terms sonification, musification and control is less consistent. They seem to define these terms as exclusive methods (Miranda et al., 2011; Venkatesh, Braund and Miranda, 2020) or methods that can be used in combination, e.g. musification with control or sonification with control (Eaton, Williams and Miranda, 2015; Daly et al., 2016; Williams and Miranda, 2018; Williams, 2019; Horrell, 2020, p.51).

To conclude, my purpose here is not to dive into philosophical arguments on terminology but to highlight some inconsistencies in the use of terms in the literature for the benefit of future BCMI researchers. To define our work, we can embrace an established classification or adapt it to form new interpretations. Based on this review and recent discussions, I believe my upcoming research in the field will benefit from a more open definition of BCMI that, rather than considering these methods to be used exclusively, allows for their combinations:

- sonification + passive control
- sonification + active control
- musification + passive control
- musification + active control
- sonification + passive and active control
- musification + passive and active control

Chapter 4

BCMI-1 Project

4.1 Project Overview

This chapter describes the project that developed the first BCMI system in this research: BCMI-1. The system has two main parts: a NeuroSky EEG headset and my NeuroSky-SuperCollider Interface software. This software acquires classified brain signals from a consumer-grade NeuroSky headset and maps them to sound control parameters of pre-composed soundscapes. I developed this software prototype in SuperCollider. The NeuroSky-SuperCollider Interface has two main parts: neurofeedback and sequencer. When using the system, these two parts run simultaneously in SuperCollider. The neurofeedback part is an audio neurogame featuring three default soundscapes that users can interact with using their classified brain signals, the eSenses. The soundscapes are pre-composed with the sequencer's graphical user interface (GUI). The mapping of eSenses to soundscape parameters makes use of both immediate and accumulative neurofeedback protocols inspired by gaming. To support meditation practices with personal musical preferences, users can create new soundscapes with the sequencer GUI and customise relevant neurofeedback protocols using textual programming. The system's design was informed by my first model (created in 2013), my initial and exploratory literature reviews, the additional workshops and courses I took, the feedback I received at events where I demonstrated the project and my informal tests. The project addressed RO2 — it developed an affordable and partially open-source BCMI system based on the literature review findings — and RO3 — it tested the suitability of this system to support meditation practices in informal NFT and artistic performance settings. The outcome of this project prompted the development of the affordable and fully open-source BCMI-2 system providing multi-channel EEG (Chapter 5) to address the limitations of BCMI-1. Although BCMI-1 did not become my research tool, I plan to port the code of its flex-time sequencer and accumulative neurofeedback protocols into the code of BCMI-2.

Project time span: September 2015—March 2018

Supporting materials:

- NeuroSky-SuperCollider Interface | SuperCollider code on GitHub.
- Video Demo Part 1 | Demonstrating the neurofeedback part of the system.
- Video Demo Part 2 | Demonstrating the sequencer part of the system.

4.2 Goals

This project aimed to redevelop the first model (Hofstädter, 2013) with particular attention to the last stages of the interfacing process: the mapping and sound control parameters.

The **project objectives** were to

1. Address the first model's weaknesses, particularly the following:
    - poor core stability
    - poor GUIs
    - limited functionalities regarding musical expressions
    - inability to connect to other EEG hardware.
2. Redesign the first model's gaming environment, including
    - neurofeedback protocols and
    - soundscapes.

4.3 Design and Development

As seen in Fig. 4.1, the system has two main parts: neurofeedback and sequencer.

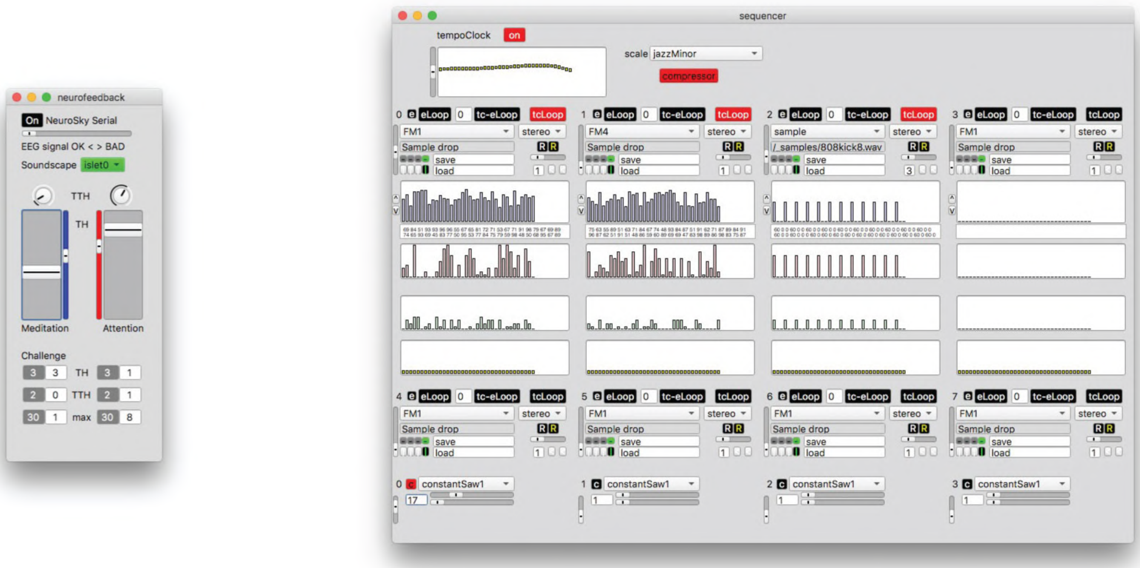

Figure 4.1: BCMI-1 GUIs: The neurofeedback (left) and the sequencer (right) parts.

I tested the system with two EEG headsets, the NeuroSky Mindset and NeuroSky Mindwave, both using a ThinkGear ASIC chip (NeuroSky Developer Program, 2014). Broadly speaking, the neurofeedback part acquires classified EEG signals from one of these headsets and, with neurofeedback protocols, controls the parameters of sounds control parameters of soundscapes. Users can interact with the three default soundscapes I designed and, if somewhat experienced in programming, create their own soundscapes and neurofeedback protocols.

4.3.1 The interfacing process

Fig. 4.2 and the paragraphs below outline BCMI-1's interfacing process in detail:

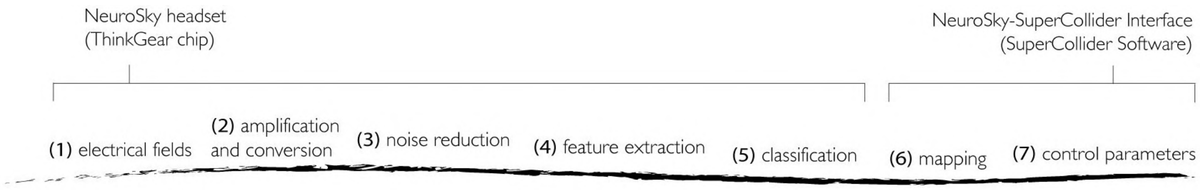

Figure 4.2: BCMI-1 interfacing steps.

(1) electrical fields

A NeuroSky headset measures electrical activity from an active electrode on the forehead (Fp1) and a reference electrode on the ear in the form of analogue signals (Fig. 4.3).

Figure 4.3: Photo of NeuroSky headsets. Mindwave (left) with additional Bluetooth headphones and Mindset (left) with built-in over-ear headphones.

(2) amplification and conversion

The difference between these two analogue signals is amplified and converted into one raw digital EEG signal by the ThinkGear ASIC chip on the headset. The sample rate is usually 128 Hz but can be as high as 512 Hz.

(3) noise reduction

The converted raw EEG signal is passed through low and high pass filters to retain frequencies between 1 and 50 Hz and is cleaned of noise and artefacts by NeuroSky's proprietary algorithms.

(4) feature extraction

Band power features (delta, theta, alpha, beta, gamma) are extracted from the clean signal with standard FFT and then analysed again for artefacts in the spectral domain by NeuroSky's proprietary algorithms.

(5) classification

While still on the ThinkGear ASIC chip, two signals are classified based on power band features and defined as the eSenses: Attention and Meditation (Fig. 4.4).

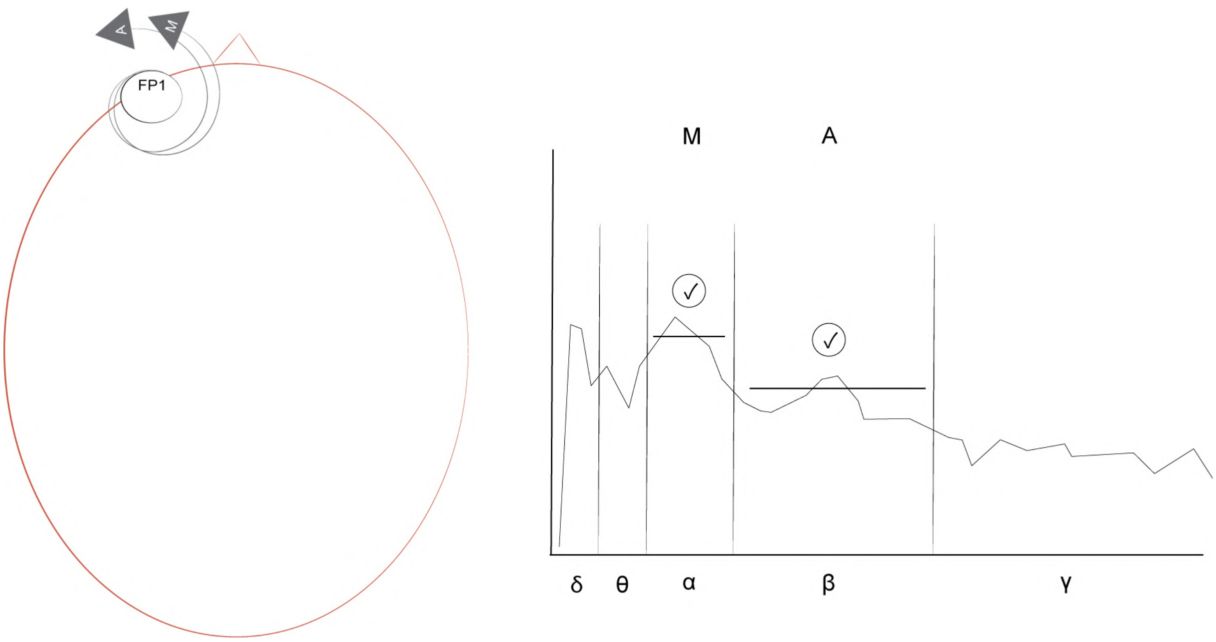

Figure 4.4: BCMI-1 neurofeedback protocol with electrode location (left) and a spectral plot (right) indicating the application of two neurofeedback indicators on the eSenses.

As the classification process of the eSenses is also proprietary, it is unclear which features or algorithms the headset uses to generate them. However, NeuroSky's support site (2011) reveals that Attention is based on beta band power features and Meditation on alpha band power features. Both eSenses are presented on a scale of 1 to 100, depending on their strengths. NeuroSky's Developer Program (2014) explains the classification process as follows:

> On this scale, a value between 40 to 60 at any given moment in time is considered 'neutral', and is similar in notion to 'baselines' that are established in conventional EEG measurement techniques (though

> the method for determining a ThinkGear baseline is proprietary and may differ from conventional EEG). A value from 60 to 80 is considered 'slightly elevated', and may be interpreted as levels being possibly higher than normal (levels of Attention or Meditation that may be higher than normal for a given person). Values from 80 to 100 are considered 'elevated', meaning they are strongly indicative of heightened levels of that eSense.
>
> Similarly, on the other end of the scale, a value between 20 to 40 indicates 'reduced' levels of the eSense, while a value between 1 to 20 indicates 'strongly lowered' levels of the eSense. These levels may indicate states of distraction, agitation, or abnormality, according to the opposite of each eSense.
>
> The reason for the somewhat wide ranges for each interpretation is that some parts of the eSense algorithm are dynamically learning, and at times employ some 'slow-adaptive' algorithms to adjust to natural fluctuations and trends of each user, accounting for and compensating for the fact that EEG in the human brain is subject to normal ranges of variance and fluctuation. This is part of the reason why ThinkGear sensors are able to operate on a wide range of individuals under an extremely wide range of personal and environmental conditions while still giving good accuracy and reliability.
>
> [The Attention eSense] indicates the intensity of a user's level of mental 'focus' or 'attention', such as that which occurs during intense concentration and directed (but stable) mental activity. ... Distractions, wandering thoughts, lack of focus, or anxiety may lower the Attention meter levels.
>
> [The Meditation eSense] indicates the level of a user's mental 'calmness' or 'relaxation'. ... [it] is a measure of a person's mental levels, not physical levels, so simply relaxing all the muscles of the body may not immediately result in a heightened Meditation level. However, for most people in most normal circumstances, relaxing the body often helps the mind to relax as well. Meditation is related to reduced activity by the active mental processes in the brain, and it has long been an observed effect that closing one's eyes turns off the mental activities which process images from the eyes, so closing the eyes is often an effective method for increasing the Meditation meter level. Distractions, wandering thoughts, anxiety, agitation, and sensory stimuli may lower the Meditation meter levels.[1]

Before the next step, the headset transmits various EEG data (including the raw EEG, band power features and the eSenses) to the computer where SuperCollider's `SerialPort` acquires, and a `Task` parses them. Then, the eSenses are smoothed and stored in global variables with the following code:

```
~neuroSkyConnect = Task(sP = SerialPort(
        "/dev/tty.MindWaveMobile-DevA",
        baudrate: 57600,
        crtscts: true);
    });
    if(~parser.isPlaying,
    ...
        ~attSig = payloadData[29];
        ~medSig = payloadData[31];
    ...
)}
```

(6) mapping

[1] Based on NeuroSky's information, we could relate the two eSenses to the two main meditation techniques discussed in the literature review (Section 3.3) and then assume that it is possible to practise concentrative meditation with the Attention and receptive meditation with the Meditation signal.

The neurogame consists of levels called 'islets'. In essence, on each islet, a neurofeedback protocol maps significant eSense behaviours to parameters of the islet's soundscape. My 2013 model had four islets: a practice islet and three sequential islets connected with a linear narrative. Apart from the practice islet, each islet had a challenge, which, when completed, allowed users to enter the next islet. The challenge on the first islet was the easiest, with a more difficult challenge on the second and the most challenging on the last (Fig. 4.5).

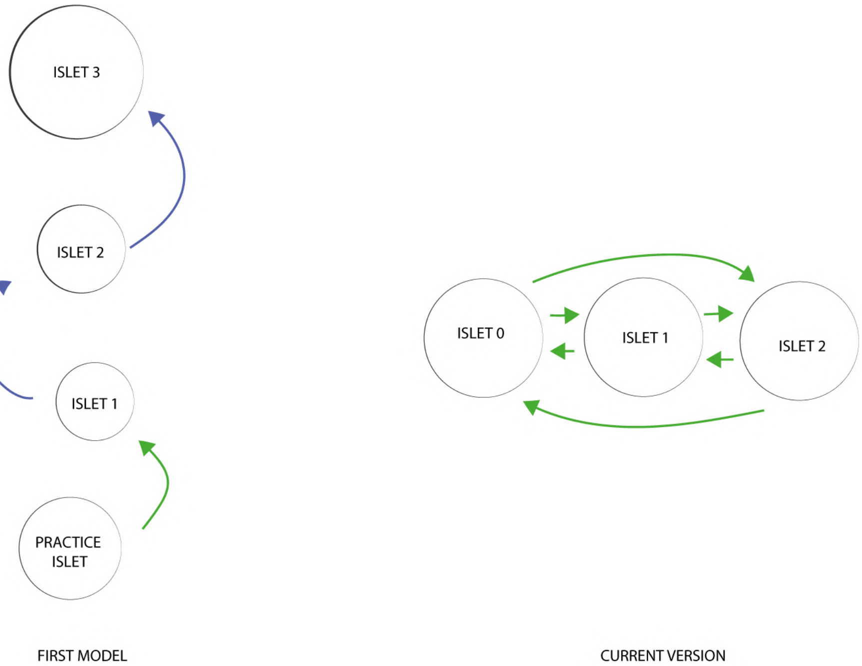

Figure 4.5: BCMI-1 gaming narratives. The first model has linear gameplay (left) in which completed challenges automatically move users to higher levels. The current version of the system (right) has levels that do not have a linear narrative; users can exit and enter islets voluntarily at any time. Green arrows indicate voluntary movements, and blue arrows indicate automatic (involuntary) movements.

The current version of the game does not have a practice islet, only three new islets. While these new islets still have challenges, the system does not automatically take users to another islet once a challenge is completed. Instead, it only triggers a 'victory sound' and allows users to stay on the islet and continue listening to the soundscape for as long as desired. In the current version, users enter the first islet when starting up the game but can exit and enter any islet voluntarily at any time (i.e. they don't need to complete the challenge on an islet to experience the soundscape of another one). Allowing users to move freely between the islets provides a more relaxed environment for practising meditation.

As in common NFT systems, a protocol in this neurogame is also based on

1. the amplitude of a classified EEG data (an eSense) and
2. the threshold (TH) on the scope of this data.

To create more engaging protocols, I added two more elements:

3. the timer and
4. the time-thresholds (TTHs).

A timer helps monitor how long an eSense stays above its TH, while a TTH is a threshold on the timer. With these four elements, the following **eSense behaviours** are monitored:

An eSense

- moves above or below its TH
- moves above its TH the X'th amount of time
- stays above its TH for X amount of time in seconds
- moves above its TTH the X'th of time.

THs are set as integers, usually between 50% and 100% on the upper side of an eSense. TTHs are also set as integers but indicate elapsed seconds. For example, if Meditation's `TH=70` and `TTH=10`, this eSense is rewarded a TTH point when it stays above its TH (70%) for 10 seconds. After 10 seconds, the TTH cycle restarts. In the first model, THs and TTHs were preset for all islets and could not be altered. In the current version, THs and TTHs can be adjusted manually by users in the GUI while playing the game.

The two functions mapping classified EEG data to musical expressions are `~rewCalcTask` and `~rewTask`. The `~rewCalcTask` function monitors the above four eSense behaviours. It is run once when entering an islet and stopped before exiting this islet. Its four primary responsibilities are to

1. monitor eSense behaviours
2. update timers
3. update reward points
4. initiate an action for completed challenges (e.g. play the victory sound).

When monitoring eSense behaviours, `~rewCalcTask` updates a six-slot array [0,0,0,0,0,0] (`var tm = Array.fill(6,(0))`) where each slot is a timer. The timers indicate the number of seconds

- [0] Attention has been above its TH
- [1] Meditation has been above its TH
- [2] Attention has been enrolled in its TTH cycle
- [3] Meditation has been enrolled in its TTH cycle
- [4] Attention has been above its TH in total on this islet
- [5] Meditation has been above its TH in total on this islet

Slots [0] and [1] restart when the monitored eSense goes below its TH, slots [2] and [3] restart when the monitored eSense goes above its TTH and slots [4] and [5] restart when entering a new islet.

Based on changes in the above timers, `~rewCalcTask` updates a 2D array, [[0,0,0,0],[0,0,0,0]] (`~rewardPoints = Array.fill2D(2, 4,(0))`), which is responsible for keeping the data on **significant eSense behaviours**. The slots in this 2D array indicate:

- [0][0] Attention currently above its TH

- [0][1] the number of times Attention has been above its TH
- [0][2] the number of times Attention has been above its TTH
- [0][3] the maximum number of seconds Attention has been above its TH
- [1][0] Meditation currently above its TH
- [1][1] the number of times Meditation has been above its TH
- [1][2] the number of times Meditation has been above its TTH
- [1][3] the maximum number of seconds Meditation has been above its TH
- [0][0] and [1][0] are updated when an eSense goes above or below a TH
- [0][1] and [1][1] are updated when the monitored eSense goes above a TH
- [0][2] and [1][2] are updated when the monitored eSense goes above TTH
- [0][3] and [1][3] are updated when the monitored eSense has been longer above its TH than earlier in the current islet [2]

Later, in this step, the system maps changes in `~rewardPoints` to control parameters of the soundscapes with `~rewTask` functions.

A challenge for an islet is defined as a 2D array, (`~toMoveVal=[[0,0,0,0],[0,0,0,0]];`). It is defined at the beginning of each islet and is continuously compared with the `~rewardPoints` array within the ongoing `~rewCalcTask` function. When all numbers in `~rewardPoints` are equal to or higher than the numbers in `~toMoveVal`, the challenge of the islet is completed. The following code demonstrates this:

```
1.do(toMoveTrueArrayCheck = ~rewardPoints >= toMoveVal);


// automove in current version disabled;
if  (toMoveTrueArrayCheck == toMoveTrueArray, er
        //stop islet and move to next islet:
        i[~presentIslet][1].reset.play;
    });
    if(victoryDone == 0,.schedAbs(t.beats.ceil, (~schedElasticOnce.value(9).play));
    })
});
```

The system uses the `~rewTask` function to create a variety of specific mappings: reward tasks (RTs). These tasks map significant eSense behaviours (`~rewardPoints`) to soundscape parameters. Several RTs

[2] [0][3] and [1][3] only update when the monitored eSense goes below the TH. This is not ideal as it should update while the eSense is above TH as well. I plan to address this issue in upcoming versions of the system.

are executed when entering an islet and stopped before exiting this islet. There are three types of reward tasks:

- (RT1) loads file(s) to be looped in a bar
- (RT2) plays (triggers) a file once
- (RT3) schedules a file to be played once at a specific beat in a bar

With significant eSense behaviours at [0][1], [0][2], [1][1] or [1][2], RT1 can rotate up to 5 files to be looped in a bar.

(7) control parameters

With the first model's linear gameplay, the islets' challenges gradually became more difficult and protocols more complex. Simpler protocols with more linear mappings in the first two islets generated soundscapes with sonification techniques. On the other hand, more complex protocols with increased multidimensional mappings in the second and third islets composed soundscapes we may musifications. Consecutive soundscapes also increased in tempo and density. For a sense of consistency, all soundscapes in the first model used similar musical instruments playing melodic expressions composed in the same musical scale. The first model's islets trained both eSenses.

The current system's three new islets (islet_0, islet_1, islet_2) also propose to train both eSenses, although with a different approach. The main difference is that users have more authority. They can

- enter any islet without the need to complete challenges in other islets
- manually change thresholds (THs and TTHs) and the challenges on each islet
- stay for as long as they wish on an islet after completing its challenge

Because users of the current system can change several aspects of the protocols, the three islets do not have specific neurofeedback goals. Instead, users are first encouraged to experiment with the default islet settings, then change them according to their meditation needs and create their own, unique islets. The key aspects of the three current islets are as follows.

islet_0's soundscape has an abstract, electronic style and could be considered more of a low-level than a high-level sonification. Its mappings have two types of immediate responses for each eSense: one that triggers sounds when eSenses go above THs (RT2) and another that maps the amplitude of the eSenses to parameters of two continuous sounds. These parameters are frequency, panning, cutoff frequency in a low-pass and cutoff frequency in a resonant low-pass filter. The soundscape proposes the synchronisation (entrainment) of brainwaves to the following:

1. the pulsations of the two continuous sounds
2. the synchronised pulsation of these two pulsations.

I will refer to these continuous sounds with the names of the synthesisers (synthDefs) with which they were made. `constantSaw1` is a somewhat sharp, pulsating sound with its fundamental frequency at

587 Hz. `constantSaw2` is a more complex sound with two pulsating components. One component is a drum-like texture with its loudest frequencies around 150 Hz. The other component is a noise texture with a variety of short percussive frequencies above 1000 Hz. The Attention eSense is mapped to one parameter of `constantSaw1`. The Meditation eSense is mapped to one parameter of `constantSaw1` and three parameters of `constantSaw2`. Attention is mapped to the cutoff frequency in `constantSaw1`'s resonant low-pass filter. When this eSense increases, the sound becomes louder and more present. Meditation is mapped to the cutoff frequency in `constantSaw2`'s low-pass filter, its oscillator frequency, and the speed of its cyclical panning position between stereo left and right. When this eSense increases, the sound is removed from its high-frequency noise textures, its pulsation slows down from 2.2 to 2.0 BPS, and its panning position becomes more fixed. Meditation also slightly changes the pulse of `constantSaw1`. Due to the nature of the synthesis in `constantSaw1`, its pulsation is ever-changing, even on the same input value. As a result, its pulse varies between 2.0 and 1.0 BPS except when Meditation is very high, making the pulse more consistent. Also, when Meditation increases, the individual pulsations of the two sounds (`constantSaw1` and `constantSaw2`) become increasingly aligned, i.e. their pulses synchronise. Also, a lower-pitched short sound is triggered when Meditation goes above its TH and a higher-pitched short sound when Attention goes above its TH. Out of the three islets, islet_0 follows Collura's (2017) suggestion most closely regarding how to best use audio feedback: the protocol uses discrete/short sounds to reward and constant sounds to provide a continuous indication of relevant changes. In general, the soundscape's slow and synchronised pulsations achieved by increasing both eSenses aim to help induce and maintain a deep meditative state characterised by low brainwave frequencies.

islet_1's soundscape is a low-density, ambient composition that uses more high-level than low-level sonification techniques. Its mappings have immediate and accumulative responses. An immediate response triggers short sounds when an eSense moves above its TH (RT2). An accumulative response plays the next file in a loop from a list of five files. The list is repeated (i.e. after the fifth file, the first in the list is played again). The following code snippet exemplifies this:

```
~usedTasks[3]=~rewTask.value(track:3,idx0:0,idx1:1,
    style:0,fromBeat:0,loadFile0:0,loadFile1:430,loadFile2:431,
    loadFile3:432,loadFile4:433).start;
```

This islet has no immediate mappings between the amplitude of the eSenses to sound parameters. Here, I aimed to help create a passive, receptive state of mind. The soundscape's low density and slow tempo aim to calm the listener while the sounds rotated by RT1 provide feedback on the eSense behaviours. As on islet_0, in addition to the above mappings, a short, lower-pitched sound is also triggered when Meditation moves above its TH, and a short, higher-pitched sound when Attention moves above its TH.

islet_2's soundscape is a 105 BPM electronic dance music (EDM)-style composition that I would consider high-level sonification. Its beat pulses at 7 BPS aiming to help entrain high-theta brainwaves. The mappings here have various immediate responses and one accumulative response. The islet only uses RT1 for mapping but in two ways. First, it loads different files when an eSense goes above and below its TH to provide an immediate response. Second, using accumulative feedback, it selects and loads the next file in a five-slot array every time the selected eSense goes above its TH. As on islet_1, the array in the accumulative feedback is repeated after the last file (i.e. after the `loadFile4` argument, `loadFile0` is loaded again). The following code provides examples of both processes:

```
~usedTasks[2]=~rewTask.value(track:2,idx0:1,idx1:0,
    style:0,fromBeat:0,loadFile0:421,loadFile1:420).start;

~usedTasks[3]=~rewTask.value(track:3,idx0:0,idx1:1,
    style:0,fromBeat:0,loadFile0:0,loadFile1:430,loadFile2:431,
    loadFile3:432,loadFile4:433).start;
```

This islet proposes to help create a more active, concentrative state of mind. With its higher density and faster tempo, I aimed to arouse and energise the listener, while the sound textures swapped with multiple RT1s provide feedback on the eSense states. In contrast to the other two islets, no short sound textures are triggered on islet_2 when eSenses move above THs with RT2 to avoid off-beat sounds that might distract users from focusing on the music. The only immediate response with RT1 is the swapping of files in four instruments when Meditation moves above its TH. Three of the four instruments trigger audio samples of percussion (kick drum, hi-hat and snare), and one of the instruments triggers audio synthesis. When Meditation moves above its TH, the style of the music changes from breakbeat to four-on-the-floor, which makes the music more energising and controlled. The accumulative response (RT1) linked to Attention rotates five melodic patterns played with a sine oscillator (`\sine`). Table 4.1 compares aspects of the three islets.

Table 4.1: Aspects of BCMI-1 islets.

	islet_0	islet_1	islet_2
style	abstract	ambient	EDM
mapping	TH and eSense amplitude	TH	TH
reward	indicators and continuous mapping	indicators	indicators
response	immediate	immediate & accumulative	immediate & accumulative
s/m	sonification	musification	musification
tempo	2.1 BPS - 2 BPS	elastic/flex-time	7 BPS
entrainment	BPS and phase	low density	BPS

4.3.2 MIDI and INScore

In addition to synthesising or sampling sounds with SuperCollider, I also experimented with sending MIDI values to other audio software (e.g. Logic Pro) and pitch values to INScore (Fober, Orlarey and Letz, 2012) with Richard Hoadley's class (Hoadley, 2011; Hofstädter, 2016d). Because many digital audio workstations and hardware can access MIDI for synthesis or sampling, this technique extends the variety of sounds available for meditation. On the other hand, as seen in Fig. 4.6, sending data to INScore allows a real person to play the soundscapes (or parts of them) on traditional musical instruments. Unfortunately, I had to postpone the development of these methods due to other research priorities.

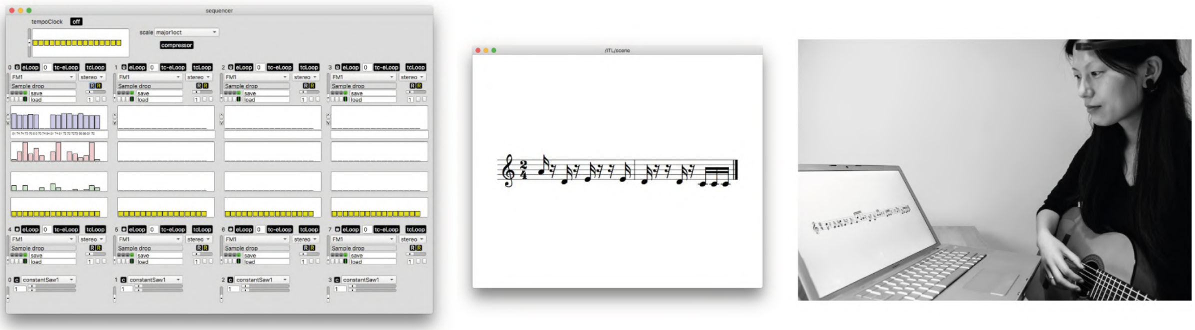

Figure 4.6: BCMI-1's sequencer GUI (left), one of its patterns visualised with INScore (middle) and the pattern played on a guitar by a musician (right).

4.3.3 Sequencer GUI

As mentioned earlier, the sequencer part of the system can be accessed as a GUI separately from the neurofeedback part. While this GUI's primary purpose is to compose and then save musical patterns into files that the neurogame can use on the islets, we can also use it for other musical activities (e.g. as a tool for live performances or to create compositions for other projects). As seen in Fig. 4.7, it has three main panels: header, enveloped synths and constant synths.

The **header panel** has three parts:

1. tempoClock - synchronises flexible timing of beats across `tracks` used in the enveloped synths panel. It can be turned on and off, and its flexible timing can be adjusted with two sliders.
2. scale - selects musical scales from a drop-down menu. Each scale is an array of MIDI numbers relevant to the selected scale. Random number generators use these arrays in the enveloped synths panel to generate arbitrary melodic expressions.
3. compressor - flattens the dynamic range of the main audio output.

The **enveloped synths panel** can control up to eight tracks. Each track can select an instrument from various synthesisers. All but the last synthesiser in the list synthesises sounds with SuperCollider's sound oscillators. The last is a sampler that plays audio files dropped onto the track's sample-drop (`DragSink`) area. To create sounds, each synthesiser requires three input parameters (`arguments`) for each sound

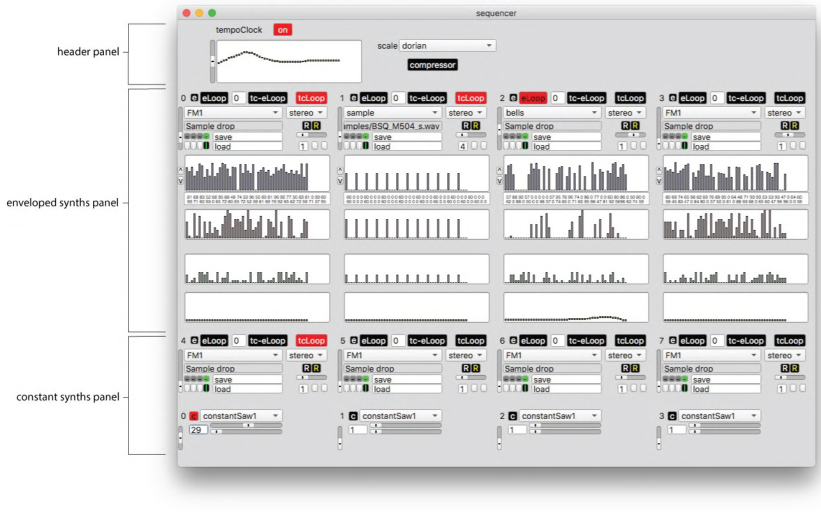

Figure 4.7: BCMI-1 sequencer GUI panels: header (top), enveloped synths (middle) and constant synths (bottom).

(note): pitch (`freq`), volume (`amp`) and length (`sustain`). We can alter these three parameters manually in the top three multi-sliders or by using buttons that populate the multi-sliders with an array of numbers. Each track can schedule notes with the tempoClock using the `~sched` function or without the tempoCock using the `~schedElasticOnce` or the `~schedElasticLoop` functions. The array of numbers 'behind' the fourth multi-slider contains `wait` times for the two tasks that run independently from tempoClock.

To save space on the GUI, only the top four instruments have multi-sliders controlling the parameters of the notes. We can save the values 'behind' the multi-sliders to the following locations:

- files that can be reloaded in the sequencer (e.g. when using the neurofeedback part)
- three separate local memories that we can use on the same track only
- one global memory that other tracks can use as well

In this panel, we can also change the output from audio (stereo) to MIDI so it can be accessed by other audio tools.

The **constant synths panel** can control parameters of up to four continuously sounding instruments. The synthesisers creating these instruments do not have envelopes like the synthesisers used in the enveloped synths panel. Instead, each can generate one long pad sound until freed manually.

4.4 Testing

I tested the system after minor and major design and development stages. Although the NeuroSky headsets only take a couple of minutes to set up, I often tested minor improvements by myself, first without, and only after some substantial work with real-time EEG. Individuals also provided feedback on major improvements at my residence and at events (Hofstädter, 2016a; 2016c; 2017). They tested the neurogame with real-time EEG and commented on the system's technical and aesthetic qualities.

On the technical side, most people wished for the system to be cross-platform and available on mobile computing devices (e.g. Android or iOS smartphones). On the aesthetic side, they were all excited about composing soundscapes that they could control with their thoughts. However, while many were confident that they could make the soundscapes in the sequencer GUI, most worried that they lacked sufficient textual programming experience to link these soundscapes to the neurofeedback part of the system.

BCMI-1 uses 'slow-adaptive' algorithms on the headset's chip to classify signals and operant conditioning when mapping these signals to sound control parameters. A complicated issue that often arose while testing was deciding how much I should tell users about the mapping (i.e. how conscious or spontaneous [unconscious] the operant conditioning should be). Should users know about and be conscious of every aspect of the reward system (e.g. what constitutes a positive or negative reward), or should conditioning happen spontaneously without users being aware of the mapping at all? Perhaps how much users should know about the system depends on the NFT goals. For instance, if users are required to focus, knowing precisely what is happening in the mapping might be helpful. However, if users want to relax and let go, they might not want to know anything about the system's technicalities.

4.5 Deployment

Apart from the demonstrations mentioned above, the system's potential use for stress management was presented in a form of a poster at the Anglia Ruskin University's 10th Annual Research Student Conference (2016). The same year, I demonstrated the sequencer GUI's ability to compose music for a collaborative piece with Dr David Belin, who researches addictions at the University of Cambridge. My work was a music video reflecting on my caffeine addiction at the time. I demonstrated the piece at the Cambridge Pint of Science Festival after Belin's presentation and at the final show at St Barnabas Church in Cambridge (2016). The sequencer is also available as a standalone application compiled with Platypus (2016). A future objective is to upload BCMI-1 to the NeuroSky's App Store, a possibility that NeuroSky welcomed in our communications. I also used the sequencer to produce two audio releases, *Compulsive Music Waves I* (Hofstädter, 2016b) and *Compulsive Music Waves II* (Hofstädter, 2018) (Figs. 4.8, 4.9).

4.6 Conclusion

Research and project objectives

The project addressed RO2 — it developed an affordable and partially open-source BCMI system based on my literature review findings — and RO3 — it tested the suitability of this system to support meditation practices in informal NFT and artistic performance settings. The main outcomes of the project are as follows:

- Functions providing timely/immediate feedback and compound/accumulative feedback.

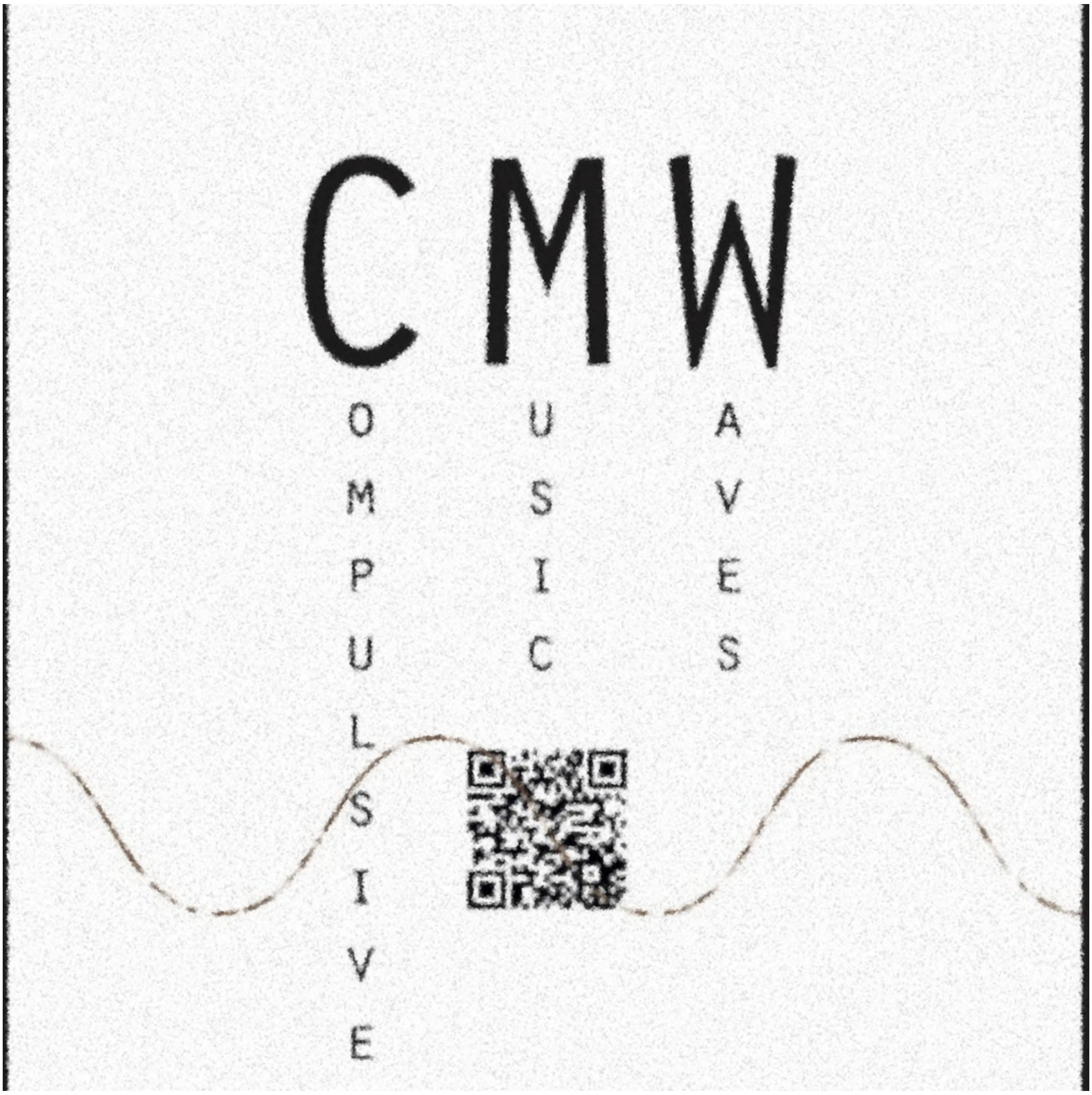

Figure 4.8: Cover art for *Compulsive Music Waves I.* (2016)

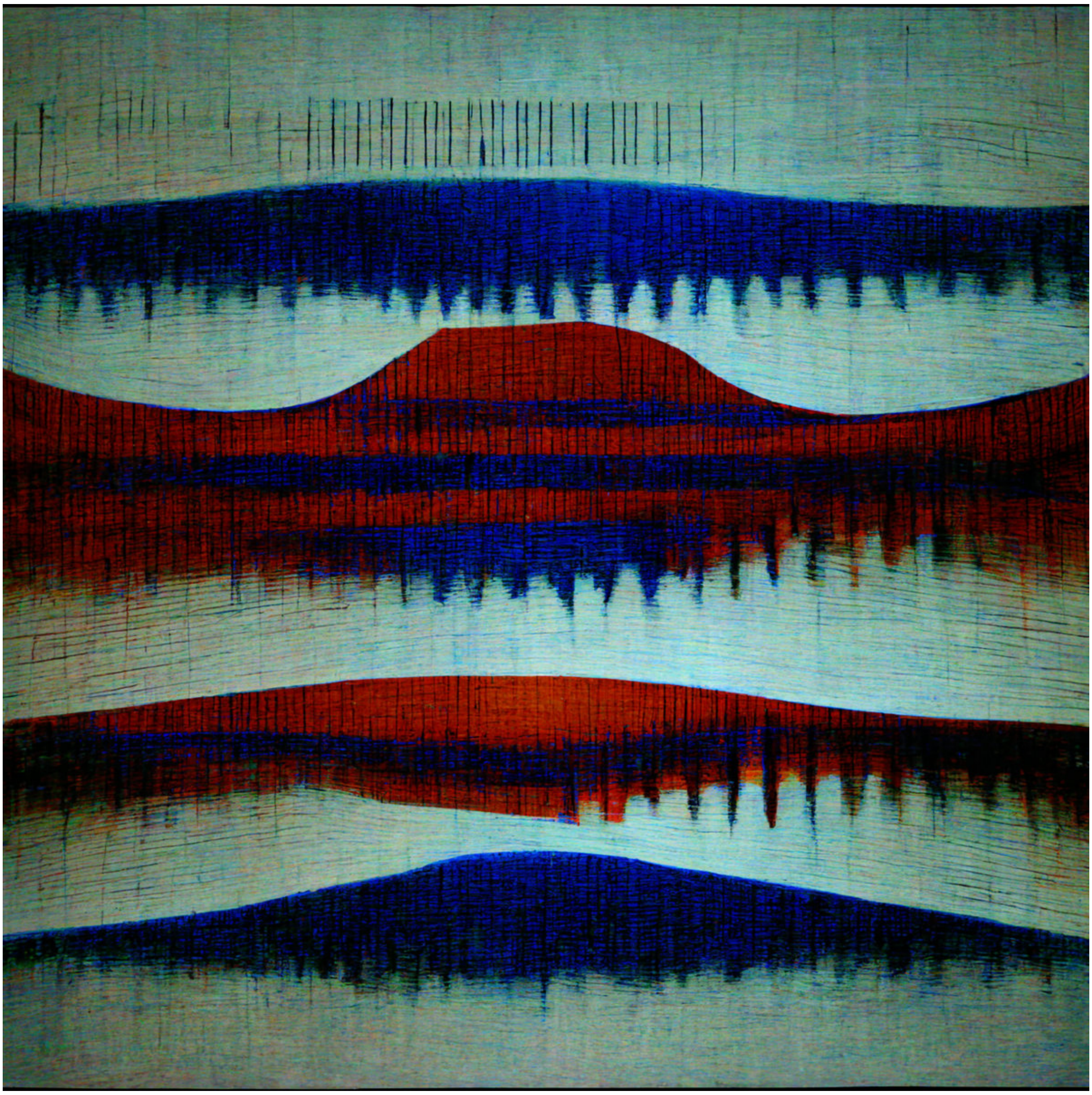

Figure 4.9: Cover art for *Compulsive Music Waves II.* (2018)

- Sound control parameters providing numerous options for personalising aesthetic and meaningful feedback through musical expressions.
- An understanding that a multi-channel EEG hardware would be more beneficial for the research than the single-channel NeuroSky hardware.

I addressed most project objectives regarding the first model's weaknesses and all regarding the gaming environment:

- With cleaner code and SuperCollider's `s.latency` and `s.bind`, the core of the sequencer (tempoClock) is more stable. Hiccups when scheduling sounds are rare and only occur when other applications (e.g. a browser or SuperCollider's help menu, are open).
- Synthesisers have been improved with more precise signal flows, better psychoacoustic amplitude compensation using `AmpComp.kr` and more distinct sounds. Also, the new `sampler` provides the use of audio samples carrying meaning that synthesisers using oscillators could not.
- The neurofeedback and the sequencer GUIs have been redesigned with improved logic and clarity.
- The gaming environment, including narration, neurofeedback protocols and soundscapes, has been redesigned according to findings from the literature.

The current version of the software is more suitable for meditation than its first model, as it addresses several aspects of how a persuasive game can help achieve goals. For instance, users have control over many aspects of the challenges, namely the thresholds (TH and TTH) and the number of points needed to complete these challenges. Users can also control the time spent on an islet even after completing a challenge. Staying for as long as desired on an islet can be helpful (e.g. when wanting to maintain a meditative state induced by a soundscape for a longer period). To motivate users to keep playing and exploring compelling sounds and methods, they are also given the option to compose their own soundscapes, which can provide further emotional and intellectual challenges.

New direction

I did not achieve one project objective: BCMI-1's ability to acquire EEG from other hardware. While this should not have been an issue, as the eSenses measured on Fp1 can provide valuable data for meditation (Fink, 2012), the proprietary algorithms involved in classifying these eSenses and the sole Fp1 location still limited my options for answering the research question. To overcome the proprietary algorithm issue, I could have developed new feature extraction and classification steps, as BCMI-1's SuperCollider code already acquires the raw EEG signal. However, primarily due to insight from my literature review suggesting that it is often locations other than Fp1 that best support meditation in NFT (Section 3.3), I began developing a new system, the BCMI-2, using another EEG amplifier, the OpenBCI Cyton. Due to this change in the research narrative, the implementation of De la Hera Conde-Pumpido's (2017) serious gaming strategies linked to social aspects has been postponed and added to Section 6.3 New Goals.

Chapter 5

BCMI-2 Project

5.1 Project Overview

In this project, I addressed RO2 by developing the affordable and open-source BCMI-2 system based on insights from the literature review, the previous BCMI-1 project and emerging questions and methods. Then, to address RO3, I tested the system's suitability to support meditation practices in NFT and artistic performance settings. In these tests, the BCMI-2 system used a combination of two methods for entraining theta brainwaves to help induce and maintain a specific meditative state, the SSC. One of these methods is computer-generated drumming with gradually decreasing tempo and decreasing rhythmic complexity, for ARE. The other is a neurofeedback protocol with auditory feedback embedded within this drumming. When using BCMI-2 myself in a performance setting, to enhance the audience's engagement I also played a frame drum, the sounds of which were processed by the system using coherence features extracted from my brainwaves. Finally, to strengthen my understanding of the effectiveness of ARE using gradually decreasing tempo and rhythmic complexity to induce the SSC, I conducted a listening study without the BCMI-2 system (i.e. without the neurofeedback protocol).

Supporting materials:

- BCMI-2 Demo 2022 (Corine Protocol Draft) | A screencast highlighting BCMI-2's specific and legible musical output with my ongoing project developing the Corine protocol for artistic performances.
- NFT Sessions with Two Participants | YouTube playlist archiving the six NFT sessions in which BCMI-2 was tested.
- Cambridge Festival of Ideas 2019 Performance Video 1 | A video collage of a screencast and two additional camera shots archiving my performance at the 2019 Cambridge Festival of Ideas.
- Cambridge Festival of Ideas 2019 Performance Video 2 | An alternative version of the above video, with additional binaural beats. The start of the video provides annotations clarifying the neurofeedback protocol used on theta at Fz.

- Practical Demo of BCMI-2 2021 | Demonstration of the practical steps required to set up and use the BCMI-2 system.

As discussed in Chapters 1 and 2, the main contribution of this research is the creation of the BCMI-2 system and recommendations based on the knowledge gained while developing and testing its suitability to support meditation practices in NFT and artistic performance settings. Section 1.3 has already explained how this system makes an original contribution to knowledge. In this chapter, I describe five sub-projects within BCMI-2. The first two projects (Sections 5.1 and 5.2) developed the system parts. The next two projects (Sections 5.4 and 5.5) tested it in different settings. Finally, the last project tested the ARE method, without using the BCMI-2 system.

1. OpenBCI-SuperCollider Interface (Section 5.2)
2. Shamanic Soundscape Generator (Section 5.3)
3. NFT Setting (Section 5.4)
4. Performance Setting (Section 5.5)
5. Listening Study Testing ARE (Section 5.6)

Fig. 5.1 visualises these sub-projects:

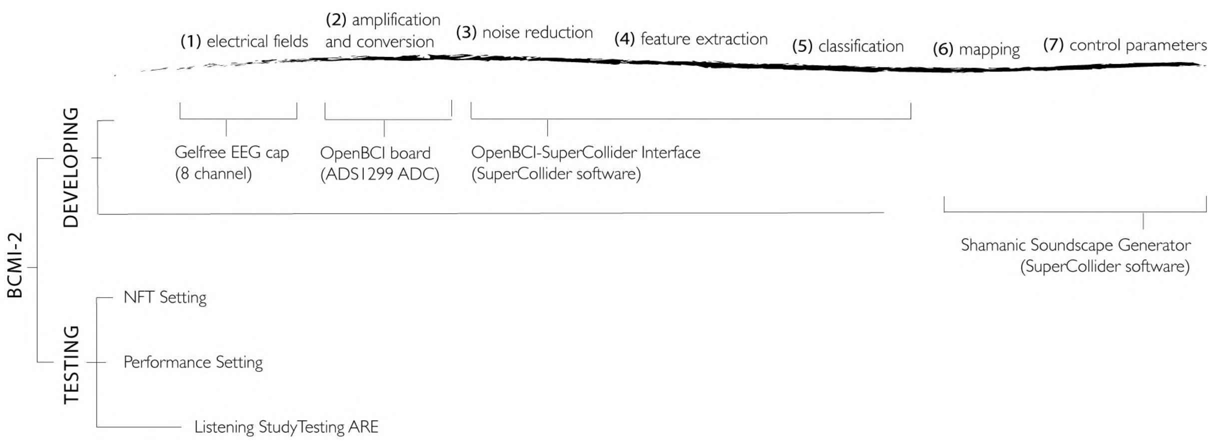

Figure 5.1: The interfacing steps of the BCMI-2 system and the sub-projects for developing and testing it.

At the end of this chapter, Section 5.7 summarises my personal experiences with shamanic journeying and engagement with the people from whom I sought guidance on shamanism. It also outlines my current approach to using ARE for deepening meditation and some new objectives to help understand the internal visual imagery encountered.

5.2 OpenBCI-SuperCollider Interface

5.2.1 Project overview

This project developed an open-source software, the OpenBCI-SuperCollider Interface, to acquire and process EEG from a multi-channel research-grade OpenBCI board within the SuperCollider IDE. The code of the OpenBCI-SuperCollider Interface was ported from the JAVA code of the open-source OpenBCI_GUI (OpenBCI, 2017a). The OpenBCI-SuperCollider Interface provides customisable functions for signal acquisition, noise reduction, feature extraction, neurofeedback protocols and plotting. When used as a part of the BCMI-2 system, it sends classified data to another software, the Shamanic Soundscape Generator, which also runs in SuperCollider. In BCMI-2, this soundscape generator software handles the last BCI steps; the mapping and sound control parameters. The project addressed RO2 — it developed part of an affordable and customisable BCMI system based on the literature review findings. The project was also informed by the outcomes of the previous BCMI-1 project (Section 5.1), emerging questions and methods and the feedback I received at events where I demonstrated early versions of the BCMI-2 system. Section 5.3 outlines the development of the Shamanic Soundscape Generator, and Sections 5.4 and 5.5 discuss the two settings in which BCMI-2's suitability to support meditation practices was tested.

Roles:

- Fredrik Olofsson (primary developer)
- Krisztian Hofstädter (secondary developer)

Fredrik is a multimedia artist and an active SuperCollider developer. I have known him through the SuperCollider mailing list since 2006 and have met him twice, in 2010 at the Berlin SuperCollider Symposium and in 2016 when he was a resident artist at the Music Department of Anglia Ruskin University. Fredrik was added to the supervisory team as an external adviser a few months after my second annual review panel in July 2017 resulted in concerns about the absence of a first supervisor for several months. Fredrik's expertise in HCI streamlined this project's design and development stages, allowing me to focus on testing and communicating my progress between projects.[1]

Project time span: April 2018—February 2020

Supporting material:

- OpenBCI-SuperCollider Interface | SuperCollider code on GitHub

5.2.2 Goals

To address RO2 — to develop an affordable and customisable BCMI system based on the literature review findings — the primary goal of this project was to address the limitations of BCMI-1 (i.e. to better equip

[1] For more information about Fredrik, visit his website at https://fredrikolofsson.com/

my research, I needed a multi-channel system with a fully transparent interfacing process). The objectives of this project were to develop a BCI system that provides

- multi-channel EEG recording
- fully transparent interfacing
- mapping to the sound control parameters of the BCMI-1's neurogame
- clear code and video tutorials to help other OpenBCI board owners test the system

5.2.3 Design & development

After exploring the Emotiv EPOC+ and the IBVA BlueVas BCI systems, I decided to further my research with the 32-bit Cyton biosensing board from OpenBCI (2015).

> OpenBCI specialises in creating low-cost, high-quality biosensing hardware for brain computer interfacing. Our Arduino compatible biosensing boards provide high resolution imaging and recording of EMG, ECG, and EEG signals. Our devices have been used by researchers, makers, and hobbyists in over 60+ countries as brain computer interfaces to power machines and map brain activity. OpenBCI headsets, boards, sensors and electrodes allow anyone interested in biosensing and neurofeedback to purchase high quality equipment at affordable prices. (OpenBCI, 2013)

There were several reasons for choosing the Cyton board for BCMI-2. First, it can measure up to eight raw EEGs, or 16 when extended with the OpenBCI Daisy Biosensing module. Second, its modular design allows connections to various headwear (e.g. EEG caps) and other types of sensors (e.g. ECG and EMG).[2] Third, OpenBCI provides open-source code for all steps of the interfacing process, including the firmware on the boards and software for processing EEGs on the computer. The firmware updates use the Arduino IDE and the EEG signal processing the OpenBCI_GUI software running in Processing IDE, which I was familiar with from my previous work. Fourth, OpenBCI projects are supported by online communities at the OpenBCI forum and relevant GitHub repositories. Finally, the Cyton board is affordable and was demonstrated to be an effective tool in academic research (Frey, 2016; OpenBCI, 2022).

First, I examined whether the Cyton board could record clear EEG with the bare-bones kit, which included the board powered by four AA batteries, gold-plated electrodes, gel, sticky tape and the OpenBCI_GUI software (running on the computer). Due to difficulties with the tape not holding the electrodes firmly enough, especially where I had hair on my head, I began experimenting with printing the Ultracortex IV 3D cap (OpenBCI, 2017b). Unfortunately, after several failed prints, I also encountered issues adapting the OpenBCI_GUI code in Processing for my purposes. Furthermore, as a result of my attempts to update the firmware on the board, I damaged it physically.[3]

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2 Researchers have often used these sensors along with EEG. See, for example, Alawieh et al. (2019) and Daly et al. (2020).

3 This damage happened when, after several unsuccessful attempts to update the Radio firmware, I soldered the FTDI connections from the converter cable to the communication pins on the board. After several attempts following suggestions on de-soldering and re-soldering with micro-soldering techniques using enamelled copper wire and a hot air gun, I managed to damage the board even further. I attribute this harm to not having the right tools nor having enough experience in micro-soldering.

To move the research forward, I got in touch with Fredrik, who was ready to investigate the issue. I shipped the damaged board to him, and he shortly repaired it.[4] Because of his enthusiasm for the project, I asked him to consider becoming my external advisor. Soon he was officially appointed. To allow us to have the same type of board at both locations (Colchester and Berlin), I secured some funding for a second board.

5.2.3.1 Which software to use for the BCI process?

Taking OpenBCI's Software Development Kits (SDKs) (2017) into consideration, we designed three systems (compared in Fig. 5.2):

1. Python-focused system
2. Processing-focused system
3. SuperCollider-focused system

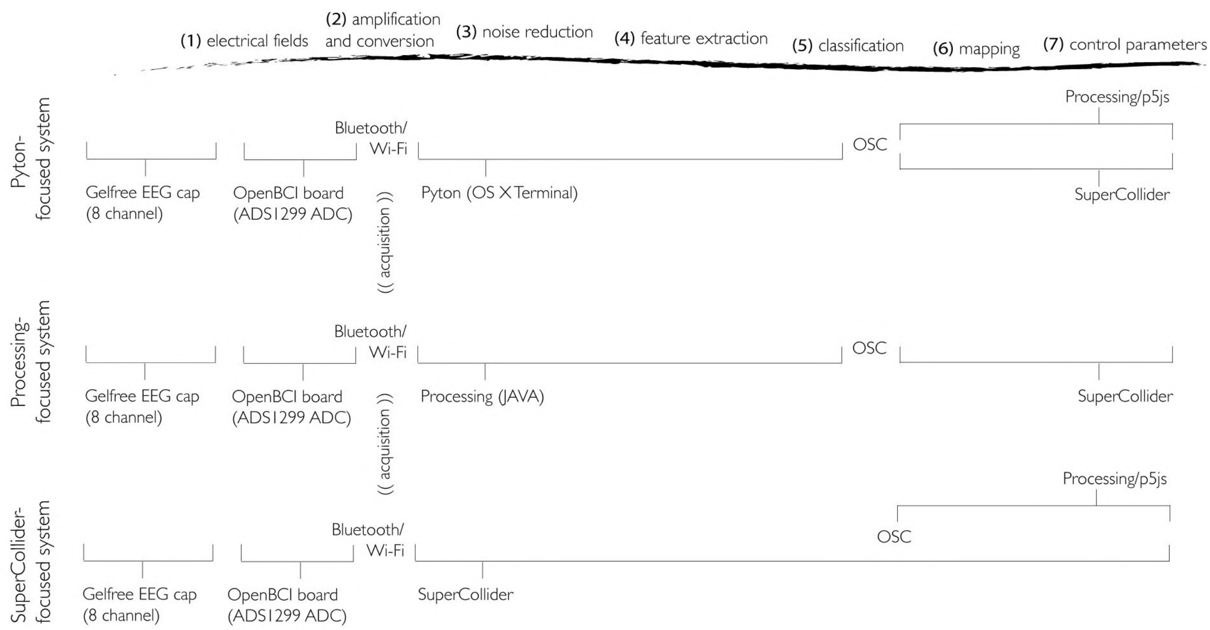

Figure 5.2: BCMI-2 interfacing considerations: Python-, Processing- and SuperCollider-focused systems.

1. Python-focused system

> Python is an interpreted, high-level and general-purpose programming language. (Python, 1986)

This system acquires raw EEG signals via Bluetooth or Wi-Fi using Python. First, we launched a Python script in the OS Terminal, where we processed EEG up to the classification step. Then, the classified data was sent to SuperCollider in Open Sound Control (OSC) messages and mapped to simple sound control parameters. An option with this system is to send classified data to Processing or p5.js for visualisation, as these applications are faster than SuperCollider for this purpose:

[4] Fredrik's documentation on this repair can be found at https://fredrikolofsson.com/f0blog/bluetooth-module-repair/.

- Bluetooth (Serial)/Wi-Fi -> Python -> OSC -> SuperCollider, p5.js/Processing

An advantage of this system is that it can largely rely on the programming of OpenBCI's Python SDK, which processes EEG signals efficiently. Another advantage is that classified brain signals can be sent to two separate software programs via OSC simultaneously, to SuperCollider for sonification and to Processing or p5.js for visualisation. However, a disadvantage of this system is that setting up the Python environment on the computer is fiddly. The setup requires installing a package manager (e.g. Homebrew, Python packages), and depending on how the operating system is configured for software development, Python versions might also need to be kept separate for clarity.

2. Processing-focused system

> Processing is a flexible software sketchbook and a language for learning how to code within the context of the visual arts. (Fry, 2001)

This system acquires EEG via Bluetooth or Wi-Fi in Processing, where it is processed up to the classification step and then via OSC sent to SuperCollider to be mapped to sound control parameters. We explored this system with two options:

- Bluetooth(Serial)/Wi-Fi -> OpenBCI_GUI (Processing) -> OSC -> SuperCollider
- Bluetooth(Serial)/Wi-Fi -> a 'NewSoftware' (Processing) -> OSC -> SuperCollider

The first option extends the OpenBCI_GUI code with a few lines that send EEG features or classified EEG to SuperCollider. In contrast, the second option creates an entirely new software program based on the OpenBCI_GUI, from which data is sent to SuperCollider. The advantage of the first option is that code for acquiring and processing EEG is available in the OpenBCI_GUI code. Its disadvantage is that the extensive code of the OpenBCI_GUI contains several functions not needed for my BCMI project. While the second option, with only the necessary code in the software, would allow the computer to focus on the processes required, it is more time-consuming to develop. An overall disadvantage of these Processing-focused systems is that they need external dependencies, which can introduce complications when users have different operating systems.

3. SuperCollider-focused system

> SuperCollider is a platform for audio synthesis and algorithmic composition, used by musicians, artists, and researchers working with sound. (McCartney, 1996)

With this system, SuperCollider handles the entire BCI process from the EEG acquisition up to the final control parameter step, with the additional option to send classified data via OSC for visualisation to another software (e.g. Processing or p5.js):

- Bluetooth(Serial)/Wi-Fi -> SuperCollider -> Processing/p5.js

The foremost advantage of this system is the clarity provided by using only one platform, SuperCollider, for the entire BCI process (after the EEG acquisition) on the computer. Having the EEG signal processing and the sound engine of the control parameters under one hood allows for dynamic and streamlined development. Furthermore, the straightforward installation of SuperCollider on all major operating systems and not needing dependencies provide a good user experience. The disadvantage of developing a system with this design is that porting relevant code from OpenBCI SDKs to SuperCollider language is time-consuming.

Python, Processing and SuperCollider have supportive communities for developers and are well-maintained platforms for serious software development. When it comes to signal processing, they all have their pros and cons. Python performs math scripts quickly but is not as efficient in real-time signal analysis. It provides good serial port and network communication support, but these communication protocols require low-level Python scripts, which can be tricky to program. SuperCollider, on the other hand, has built-in features for real-time signal processing (e.g. filters and FFT), although these features are mainly documented for audio processing. Processing is primarily made for graphics, so it relies on external dependencies for math and signal processing. With regard to communication protocols, Python and Processing can communicate via User Datagram Protocol (UDP), Transmission Control Protocol (TCP) and OSC, while SuperCollider can only use UDP and OSC. They all support Bluetooth communication; however, only Python and Processing can link to the Wi-Fi shield due to a TCP issue in SuperCollider. SuperCollider not supporting TCP is a drawback as TCP is used in the OpenBCI Wi-Fi shield firmware. After several experiments and discussions regarding each system, we chose to develop the SuperCollider-focused system further.

5.2.3.2 The interfacing process

This project focused on developing the OpenBCI-SuperCollider Interface to deal with the initial steps (1-5) of BCMI-2, the system I envisioned to be suitable to support meditation in NFT and artistic performance settings. These five steps are visualised in Fig. 5.3 and detailed below.

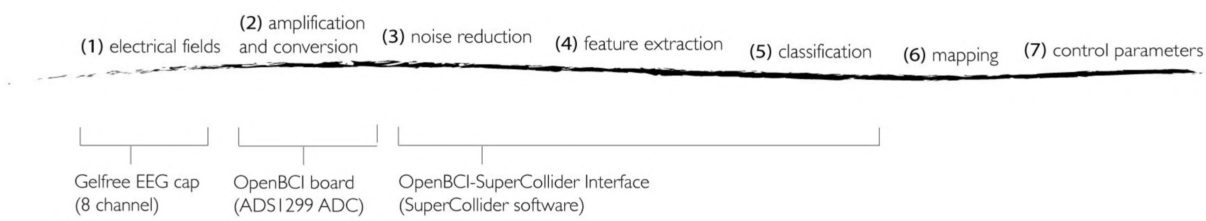

Figure 5.3: Interfacing steps of the OpenBCI-SuperCollider Interface.

(1) electrical fields

The Gelfree-S3 EEG recording cap by Greentek (2018) measures electrical activity from eight selected locations with sintered Ag-AgCl electrodes as analogue signals using ground (GND) at location AFz and reference (REF) at CPz (Fig. 5.4). All electrodes are soaked in 2.5% saline water. The 10 electrodes are connected to the Cyton board pins with a cable loom clipped to the user's clothes. I introduced the clip to help reduce artefacts in the EEG made by head movements.

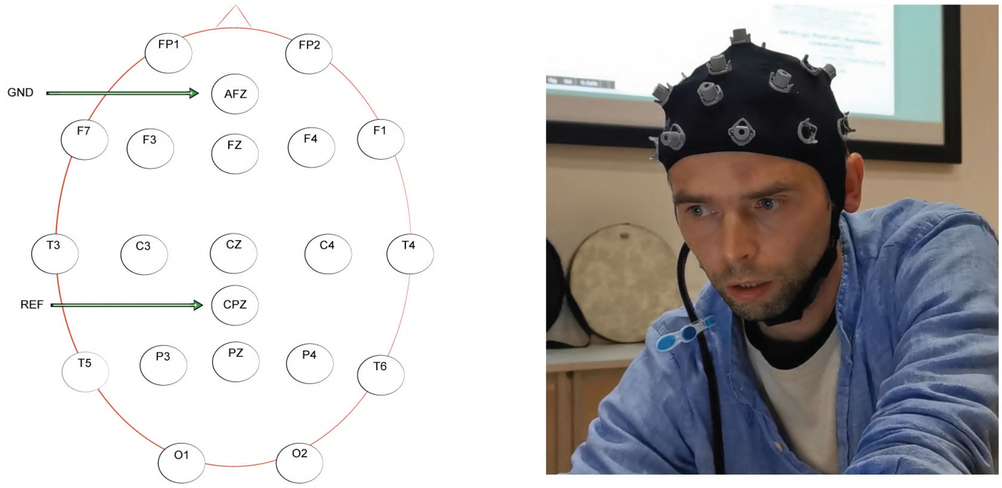

Figure 5.4: Available electrode locations on the Greentek Gelfree EEG cap, showing the ground (GND) and reference (REF) used in this research (left). A photograph (right) shows this cap on my head, with the cable loom clipped to my shirt.

(2) amplification and conversion

On the board, the eight EEG signals are referenced to the reference signal, amplified and converted from analogue to digital with the ADS1299 chip providing 24-bit channel data resolution.

After this step, the computer acquires and parses the EEG signals: First, the board's RFDuino module sends the eight digital signals via Bluetooth serial-data transmission at 250 Hz to the RFDuino USB dongle plugged into the computer. Then, the `CytonSerial.sc` class of the OpenBCI-SuperCollider Interface acquires the signals from this dongle with the SerialPort object by using the operating system's FTDI driver. Finally, the same class parses the received signals to make them accessible for further signal processing. This class is based on the Cyton Board SDK.

(3) noise reduction

The interface's Butterworth bandpass filter attenuates frequencies below 1 Hz (to remove DC offset) and above 50 Hz (to help concentrate on the frequencies needed). Also, its 50 Hz notch filter attenuates the mains (electric power line) hum. (Relevant code can be found in the `DataFilterBandpass.sc` and `DataFilterNotch.sc` files.)

(4) feature extraction

After noise reduction, the first sort of features extracted from the EEGs are the time series. As seen in Fig. 5.5, this feature can be visualised in a GUI (e.g. to examine the signals' wave shapes for irregularities and to help reduce impedance in the electrodes before NFT and artistic performances, ideally below 10 kOhms). The second sort of features are the frequency spectrums extracted with FFT, again from all EEGs (Fig. 5.6). The third sort of features are energy medians (the brainwaves) of some EEGs' selected frequency bands (Fig. 5.7). In my NFT setting, I extracted a theta energy median from Fz and a gamma energy median from Pz. In my performance settings, I only extracted theta energy medians, however, from all eight active EEGs. I used one of these signals in my neurofeedback protocol and four others for

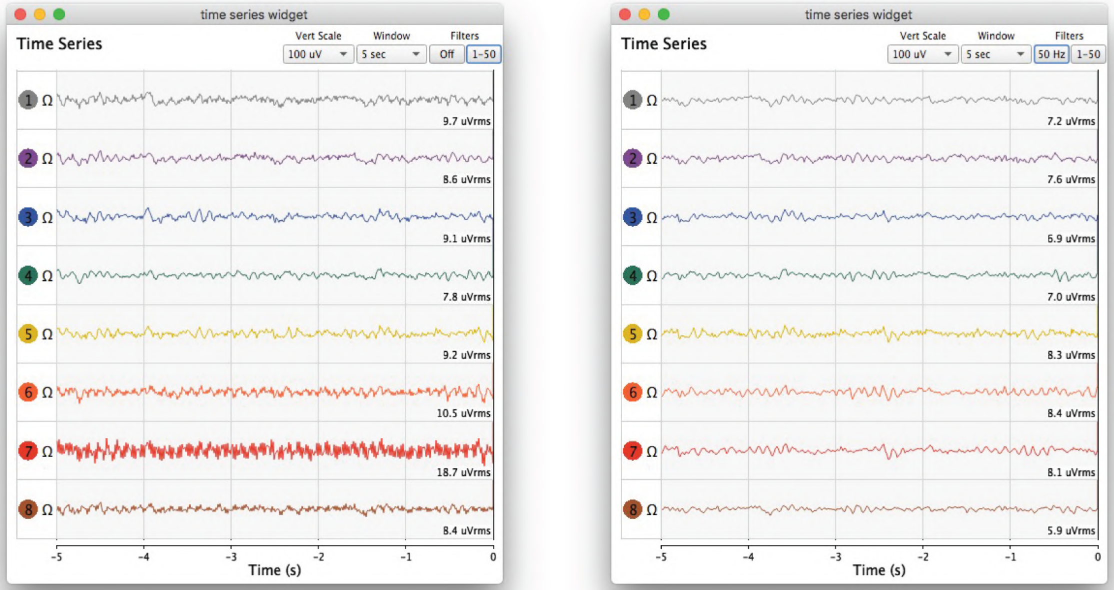

Figure 5.5: Time series plot of the OpenBCI-SuperCollider Interface with only the 1-50 Hz bandpass filter enabled (left) and with an additional 50 Hz notch filter (right).

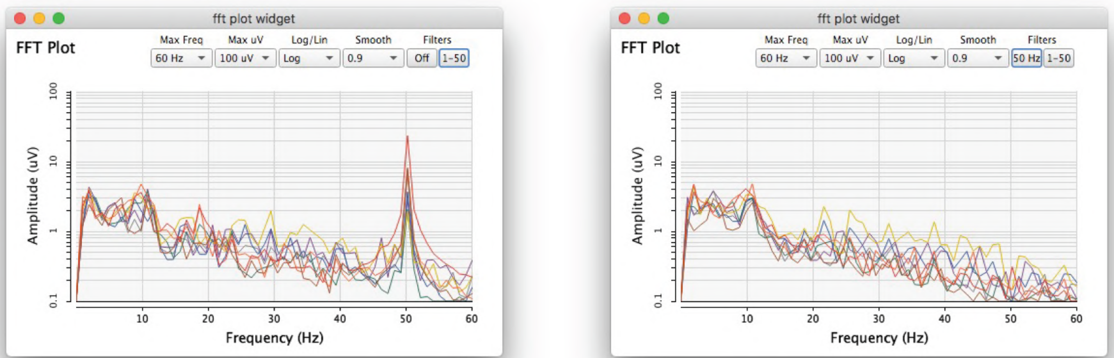

Figure 5.6: FFT plot of the OpenBCI-SuperCollider Interface with only the 1-50 Hz bandpass filter enabled (left) and with an additional 50 Hz notch filter (right).

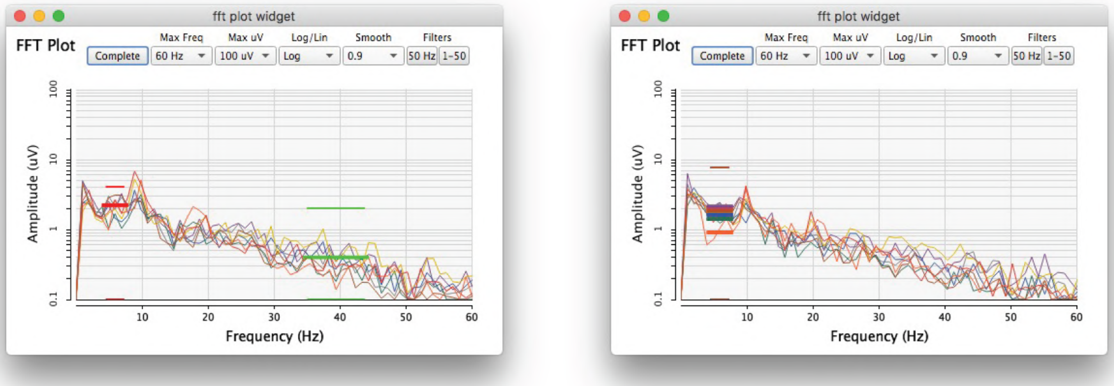

Figure 5.7: FFT plot of the OpenBCI-SuperCollider Interface showing theta and gamma energy medians (left) with neurofeedback thresholds for theta at 4 uV (top slim red line) and threshold for gamma at 2 uV (top slim green line). Eight extracted theta medians (right) with a threshold for one at 7.5 uV (top brown line).

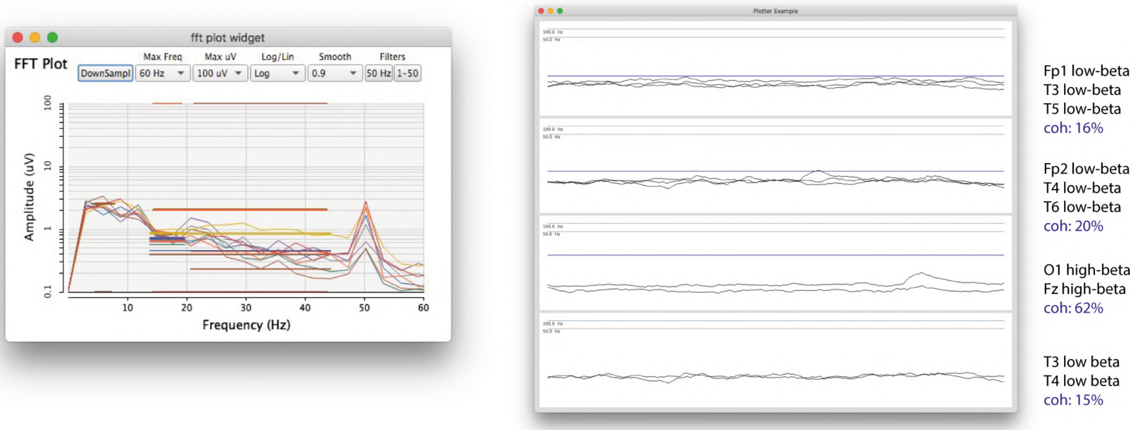

Figure 5.8: FFT plot of the OpenBCI-SuperCollider Interface showing 12 band energies (left) and selected energies compared for phase coherence (right). Phase coherence is indicated as inverted percentages (100 percent = no coherence; 0 percent = total coherence).

the following feature extraction method. The fourth sort of features extracted are coherences between specific bands' energy medians (Fig. 5.8). While previous versions of the software (e.g. the one used in my performance setting) could only extract amplitude coherence, current versions can also extract phase coherence.[5]

(5) classification

I classified increased theta energy median at Fz as a sign of an emerging deep meditative state, the SSC. To help myself and others induce and maintain this state, I used a single-channel neurofeedback protocol with a manually adjusted threshold. In the BCMI-2 system, this threshold is a neurofeedback indicator playing an auditory reward sound (a shaker sound embedded in computer-generated drumming). The drumming and the shaker sound are generated with the Shamanic Soundscape Generator in real-time with ARE. I describe this generator in Section 5.3.

5.2.3.3 Recording and loading EEG for off-line data analysis and plotting

In addition to acquiring real-time EEG data from the board, the software can also synthesise or load data from files. It can load data that it previously saved (or that was saved by other software programs following the same comma-separated formatting convention). Similar to the OpenBCI_GUI, the OpenBCI-SuperCollider Interface can record raw EEG and accelerometer data into text files during real-time sessions. It can also record additional data into these files (the 'BCMI data files'). This additional data may include extracted features or sound control parameters from the Shamanic Soundscape Generator. We can easily add extra data to the default format by using the `~rec.extra` method of the `DataRecord` class:

```
var recorder= DataRecord(~openbci);
    recorder.extra=[~hiBandEnergy,~bandEnergyAvg[0],~bandEnergyAvg[1],
        ~bandEnergyAvg[2],~bandEnergyAvg[3],~bandEnergyAvg[4],~bandEnergyAvg[5],
        ~bandEnergyAvg[6],~bandEnergyAvg[7],~phaseSync1,~phaseSync2,
        ~currentForestDepth,~timer[0],~timer[1],~timer[2],~timer[3]];
~rec= recorder.start;
```

In addition to simply replaying the BCMI data files, the OpenBCI-SuperCollider Interface can also plot them. After manually adjusting the plotter (`nf-plotter-example.scd`) to fit the data file format, it can plot band energies, threshold changes, coherences between selected energy bands, and even the waveform of audio files.[6]

[5] While I extracted both theta and gamma medians in my NFT sessions, I only used the theta median to control sound. The gamma was only visualised, not mapped to any sound. While I used amplitude coherence to spatialise sound in my performance settings, my forthcoming projects will use phase coherence for this control. Relevant code can be found in the `openbci_gui_timeseries.scd`, `openbci_gui_fftplot.scd` files and the `openbci_gui_fftplot_with_neurofeedback` folder.

[6] Shortening the format is possible by sub-classing the `DataRecord` class. The simplest way to subclass `DataRecord` is by duplicating its code in a new .sc file (e.g. called `myDataRecord`) and then making modifications in this new file. We can find examples of this BCMI data file in Appendix 2. Sections 5.4 and 5.5 provide plot examples (Figs. 5.18, 5.19, 5.30).

5.2.4 Testing and challenges

To streamline development, I reproduced relevant aspects of Fredrik's operating system on an appointed partition of my computer's hard drive. We both worked with the same type of MacBook Pro laptop. For the entire project, we used macOS Sierra 10.12.6 and the same version of Python, Processing, SuperCollider and dependencies where needed. Our communication was primarily via email, often supported by screencasts. First, code drafts were either attached to emails or embedded in the email text. Later, I uploaded screencasts of my tests to Dropbox or YouTube (Hofstädter, 2019a). Finally, we pushed software updates to the project's GitHub repository. Testing code often required comparing raw and spectral EEG visualisations between SuperCollider and OpenBCI_GUI with several methods, including closing eyes, tensing jaw, blinking eyes, and touching the computer screen to generate electrical noise.

My attempt to use the bare-bones kit failed. Using only gel and tape with an electrode where hair was present did not provide reliable signals. Sometimes, even minor head movements could contaminate the signals. Therefore, I decided to 3D print one of OpenBCI's 3D headsets (2017b). Unfortunately, my printing encountered several technical complications, primarily due to not having access to a reliable 3D printer. As this caused further delay to my progress, I purchased the Greentek S1 Gelfree EEG cap, which fortunately provided clear and stable EEGs. Due to the issues with corrosion and long electrode soaking time required with this S1 model, I discussed the improved S3 with the manufacturers and research institutes that have used both caps and developers of BCI systems. As their feedback on the new model was positive, I purchased one and used it in the last development cycles of the project. While the S3 was slightly more expensive than the S1, its electrode soaking time is shorter, and there is no corrosion on the cap (so far) either.

I introduced the following improvements to my setup. First, one lithium polymer (LiPo) battery now powers the board instead of four rechargeable AA batteries. The LiPo battery not only has a much longer life but is also smaller and can be charged faster than AA batteries. I can also recharge the new battery via USB, so carrying a bulky AA charger around for demonstrations and performances is no longer needed. Second, I put the board in a 3D-printed enclosure. I designed this enclosure based on the `Ultracotex Mark IV Board Mount` and `Cover` stereolithography (.stl) files (OpenBCI, 2017b). One of my customisations made the enclosure higher to allow the Cyton board and the Wi-Fi shield to fit inside. Another customisation was a small window on the side to improve the connection between the radio module on the Cyton, and the radio module in the USB dongle plugged into the computer. Also, the enclosure now has a screw nut glued to the bottom to allow stable fixing on a camera tripod. Having the board on a tripod helps adjust the height and angle needed for different setups (e.g. sitting and standing), and it also helps electrically ground the board. The tripod's quick-release function is also handy for longer presentations or performances during which the user needs to move more freely without the tripod. Finally, the enclosure protects the board from occasional saline water dripping from the EEG cap.

After stably using Bluetooth communication for a while, we decided to develop Wi-Fi communication to provide more accurate EEG data with a higher sample rate. However, working with Wi-Fi turned out to be more complex than working with Bluetooth. It requires a Wi-Fi shield plugged into the board and, ideally, a designated router between this shield and the computer. Furthermore, we must customise the firmware on this shield when using SuperCollider for EEG acquisition. After several attempts to make the Wi-Fi communication work, I was reminded of the Wi-Fi shield's disclaimer. It stated that the shield was not considered a finished end product, and its intended use was only for evaluation, demonstration and engineering development purposes (OpenBCI Archive, 2019). The OpenBCI Support also informed me that the shield had been working seamlessly with the 8-bit Ganglion board; however, due to a firmware imperfection, it had been found problematic by many Cyton board users. Therefore, developing the Wi-Fi transmission has been on hold but is planned to be revisited with the other OpenBCI board, the Ganglion.

The development of the feature extraction steps encountered two significant challenges. First, after porting the OpenBCI_GUI code to SuperCollider's client-side (sclang), it turned out that this client-side was too slow for the required DSP. Therefore, the code had to be rewritten into C++ for SuperCollider's server-side (scsynth), which provided faster processes. Secondly, developing the code to extract phase coherence was also challenging due to the advanced programming expertise required and the time pressure from a public event where I planned to use this feature. I was supposed to perform with this feature at the 2020 Cambridge Science Festival using my most recent neurofeedback protocol inspired by neuromarkers linked to shamanic trancing (Flor-Henry, Shapiro and Sombrun, 2017). Although my performance was cancelled, with the help of the SuperCollider Forum (2019), this feature extraction is now functional and ready for public performance. I briefly outline this neurofeedback protocol (the Corine protocol) in Appendix 5.

Besides using the OpenBCI-SuperCollider as a part of the BCMI-2 system, I also used it to monitor EEG while listening to audio releases by the Monroe Institute (1962a) and Andrej Hrvatin (2019), as well as my own live or pre-recorded drumming. These experiments informed the development of the OpenBCI-SuperCollider with a variety of valuable insights, for instance regarding (1) how I could use sound effectively in NFT, (2) the possible complications with using in-ear Bluetooth headphones while simultaneously recording audio, video and BCMI data on one operating system and (3) unwanted EEG artefacts from parietal and occipital lobes from users lying down instead of sitting upright. Another disadvantage of lying down to sitting upright during a session is that when lying down, impedance increases faster in the electrodes. Gravity aids adhesion when sitting and works against it when lying. Suggestions to overcome this issue include covering the EEG cap with a shower cap to slow water evaporation and using a roll-shaped pillow that pads the neck while raising the head slightly above the mattress.

5.2.5 Deployment

I first demonstrated the OpenBCI-SuperCollider Interface with an early prototype of the Shamanic Soundscape Generator at the Audio Engineering Society's 2019 International Conference on Immersive and Interactive Audio in York (Hofstädter, 2019b). Later that year, with a more updated version of the soundscape generator, I tested its suitability for helping meditation practices in NFT and artistic performance settings (Sections 5.4 and 5.5). The code for the software is open-source and available for others to test on GitHub (Olofsson and Hofstädter, 2019).

5.2.6 Conclusion

Research and project objectives

The project addressed RO2 — it developed one part of an affordable and open-source BCMI system based on the outcomes of the previous BCMI-1 project, my literature review and the feedback I received from events where I demonstrated versions of the system. The primary result of this project is a new software that

- Acquires and processes multi-channel EEG.
- Has fully transparent, open-source code (it is free).
- Can be effortlessly linked within the SuperCollider IDE to another software that handles the mapping and sound control parameter steps of a BCMI (the Shamanic Soundscape Generator) to support meditation practices in NFT and artistic performance settings.
- Can save BCMI data files, including raw EEG and custom data (e.g. features extracted during NFT sessions).
- Can replay and plot BCMI data files for off-line analysis (or artistic work using off-line EEG data).
- Can be used to classify EEG signals to be acquired by another software to handle the remaining BCMI steps (perhaps via OSC).
- Uses hardware and other essential accessory parts, which in 2019 cost under £1000. In 2022 they will cost under £1400. These parts include the OpenBCI Cyton board, the Greentek Gel-free EEG cap, two rechargeable batteries, distilled water and salt.

All project objectives were addressed and demonstrated successfully, apart from the software's ability to connect to the neurogame developed in the previous BCMI-1 project and the making of concise video tutorials to encourage researchers to experiment with the software. I did not address the neurogame-related objective because of my shifted interest in composing soundscapes with ARE. Writing new code with a specific focus on generating ARE appeared to be less time-consuming than amending the sequencer of BCMI-1 to generate ARE. However, the objective regarding the video tutorials is still important; hence, I plan to address it as soon as possible.

New objectives

New hardware-related objectives are to

- test the software with the 8-bit Ganglion board (4 EEG channels) and with a Daisy module added to the Cyton board (16 EEG channels)
- link a heart-rate monitor to the system to provide more comprehensive biofeedback
- continue developing the Wi-Fi communication to have a faster alternative to Bluetooth

New software-related objectives are to

- program a function that calculates neurofeedback success rates to adjust neurofeedback thresholds automatically (Dhindsa et al., 2018)
- program a function that extracts standardised LORETA features to help monitor the cortical connectivity of the brain (University of Zürich, 2001)
- program a function that extracts ERPs to help monitor how the brain processes specific audio signals and understand how directed attention has an impact on entrainment (Rosenboom, 1997, p.36)
- send extracted EEG features via OSC to Processing or p5.js, e.g. to visualise the frequency domain with the addition of a time dimension to create a waterfall analysis similar to the one in IBVA software (Fig. 5.9)

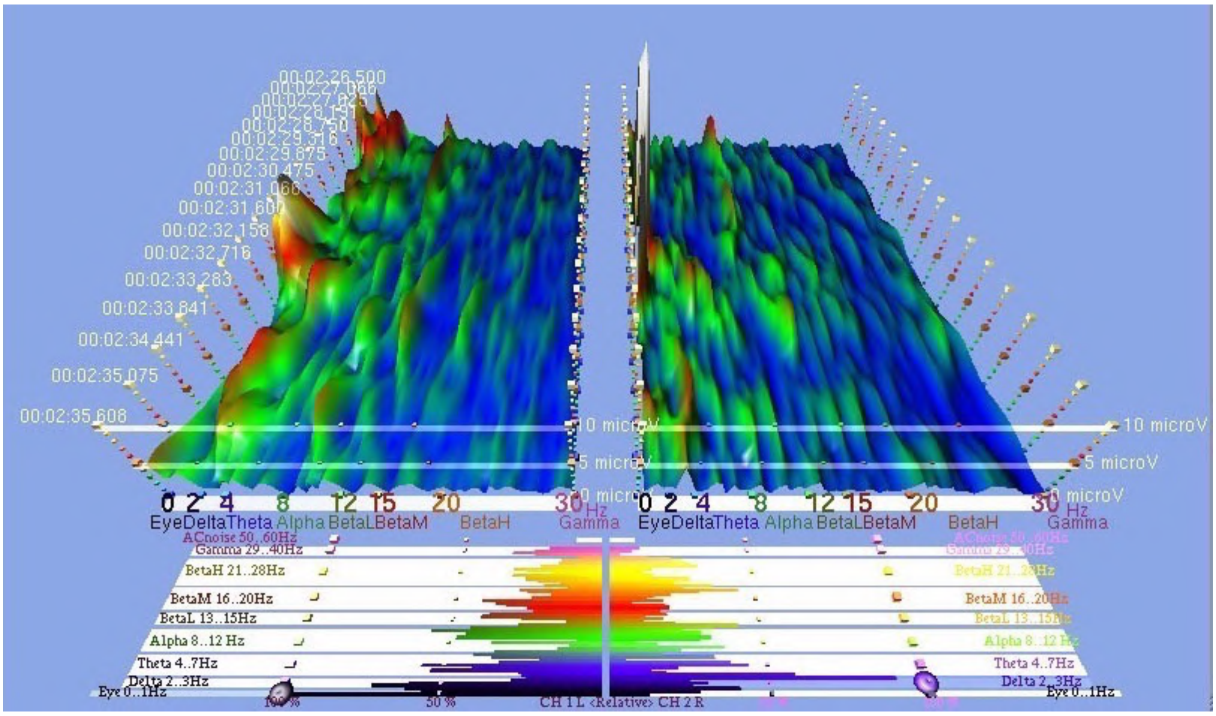

Figure 5.9: Waterfall FFT analysis in IBVA software.

- investigate how the FEELTRACE instrument recording users' perceived emotions (Cowie et al., 2000) could be added to the system without introducing artefacts to the EEG
- continue investigating how impedance could be monitored while recording EEG signals (OpenBCI

Forum, 2019)

- compare the data plotted in SuperCollider with data plotted in Matlab
- make conscious video tutorials demonstrating the interfacing process

I hope the project's open-source nature will attract other researchers who can help address these new objectives and develop new software for the remaining BCMI steps (i.e. alternatives to my Shamanic Soundscape Generator). Next, in Section 5.3, I outline the development of this soundscape generator, which, together with the OpenBCI-SuperCollider Interface, forms the BCMI-2 system. Then, Sections 5.4 and 5.5 outline how I tested this system's suitability to support meditation practices.

5.3 Shamanic Soundscape Generator

5.3.1 Project overview

This project developed the open-source Shamanic Soundscape Generator software in SuperCollider IDE. It acquires classified EEG from the OpenBCI-SuperCollider Interface and, using its neurofeedback protocol, triggers a discrete reward sound for operant conditioning. This sound, the control parameter, is embedded in soundscapes generated with ARE. The parameters of the soundscapes, including the reward and ARE sounds, are customisable. Running both software, the OpenBCI-SuperCollider Interface and the Shamanic Soundscape Generator in the same IDE provides straightforward mapping with global variables and numerous options for further development, especially with regard to the musical aspect of BCMI-2. The project addressed RO2 - it developed part of an affordable and customisable BCMI system. To answer my research questions, I tested the system's suitability to support meditation in NFT and artistic performance settings (Sections 5.4 and 5.5).

Project time span: February 2019—April 2020

Supporting material:

- Shamanic Soundscape Generator | SuperCollider code on GitHub

5.3.2 Goals

To address RO2 — to develop an affordable and customisable BCMI system based on the literature review findings — the objectives of this project were to create a software program that

- acquires classified EEG from the OpenBCI-SuperCollider Interface effortlessly
- provides customisable mapping of this classified EEG to sound control parameters
- generates a soundscape with customisable ARE, of which the neurofeedback reward sound (the sound control parameters) is an integral element
- has fully transparent BCI steps.

These objectives were informed by technical aspects of the OpenBCI-SuperCollider Interface, relevant literature review findings and personal conversations with rhythmic entrainment expert Jeff Strong and NFT practitioners Jeff Tarrant and Tony Steffert.

5.3.3 Design and development

To address these objectives, I built the Shamanic Soundscape Generator in SuperCollider, the same IDE as the one used for building the OpenBCI-SuperCollider Interface. Running the two software programs in parallel in SuperCollider allows for straightforward mapping and scaling of classified EEG to sound control parameters via global variables.

As discussed in Chapter 1, existing NFT systems mainly focus on giving visual feedback (Steffert, 2018, p.136) and where they provide options for auditory feedback, these options are often limited, not allowing the development of engaging musical experiences (i.e. they do not employ the wide-ranging capabilities of music that could help induce and maintain the desired states of mind) (Miller, 2011; Mealla. et al., 2014; Steffert, 2018, p.84). Although the auditory feedback from the neurofeedback protocol used in BCMI-2 is simple, it is embedded as an integral element within the other entrainment method, ARE. Therefore, I hypothesised that the combination of these two methods would help increase theta waves and induce and maintain an SSC in my experiments.

I first developed the ARE component of the software, inspired by the works of Jeff Strong (Section 3.4). I programmed a sequencer to play sounds in various rhythmic patterns at different tempos. The sounds triggered can be synthesised or pre-recorded audio samples, allowing for the use of auditory stimuli with specific meanings and associations. Specific meanings associated with the triggered sounds should aid further immersion into the desired state of mind. For example, if the idea is to relax the listener, sounds used in the soundscape should probably not be harsh or unpleasant. However, if the idea is to create and maintain an alert, mindful state of mind, then harsh, unpleasant, or even frightening sounds might be helpful. Although it was technically possible, I resisted the idea of composing music in my usually preferred style (melodic EDM). Instead, I chose a minimal approach in order to have a more manageable number of variables in the music for later analysis. To add meaning to the soundscapes, I took ideas from the shamanic world, specifically from shamanic journeying, a type of guided meditation often accompanied by monotonous auditory entrainment (Section 3.4.3).

5.3.3.1 Soundscape structure

I envisioned my soundscapes as journeys to the middle of an imaginary forest through several layers called 'levels'. A soundscape starts outside the forest and moves gradually inwards. At the end, when the journey reaches the middle of the forest, a 'call back', with drumming that suddenly slows down and changes in rhythm, returns the listener to the outside of the forest. While moving towards the middle of the forest, the drumming becomes gradually slower, more repetitive, less variable and slightly louder. Before generating a soundscape, levels could be set up with random durations to create a unique narrative or with exact durations to help compare results in analysis later Fig. 5.10.

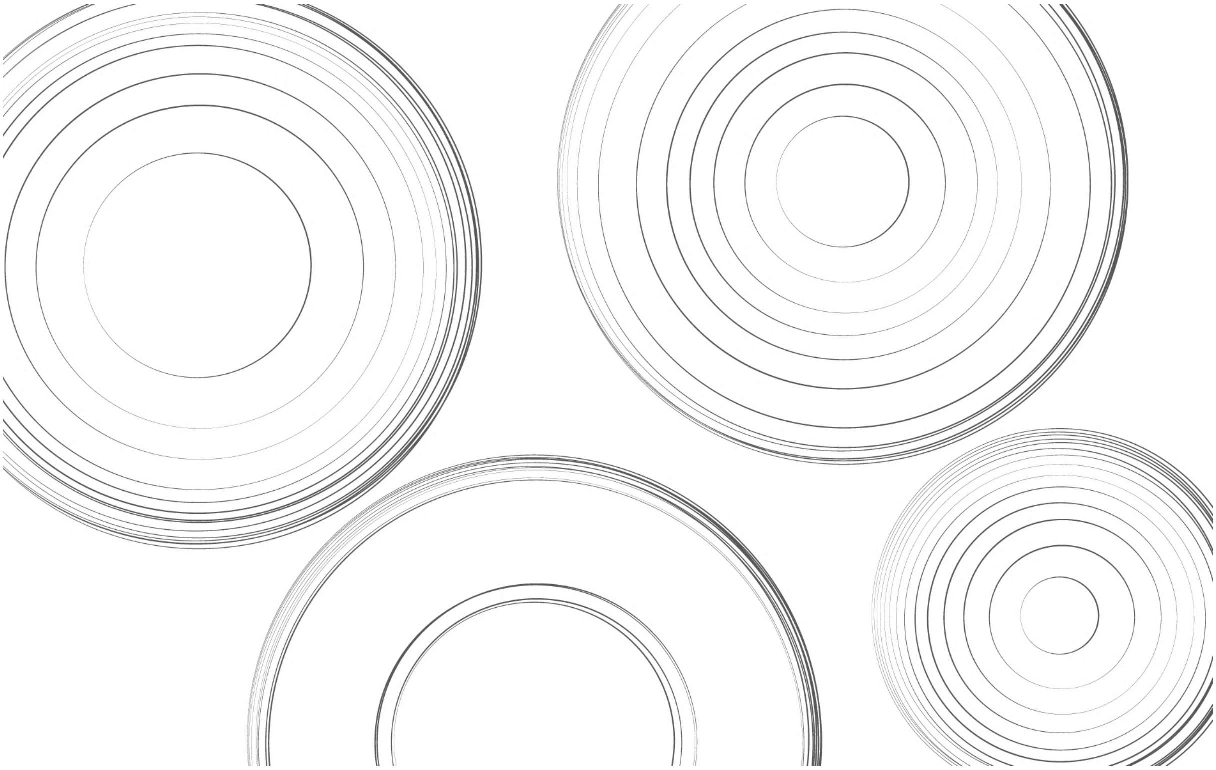

Figure 5.10: The duration of soundscape levels can be generated randomly (top left and bottom left) or with exact, predefined values (top right and bottom right). Three soundscapes are 30 minutes long, while one (bottom left) is 20 minutes long.

The soundscapes generated have three tracks: noise, drum and shaker (Fig. 5.11):

Noise track

Each level in this track starts with 'a call', represented by a short horn sound, while a long sound slowly fades in at the beginning and then out at the end of the level. The soundscapes are all set up with horns that sound the same in each level, but the noise sounds are different: their low-pass filters' cutoff frequencies shift at the start of each level. For example, in the NFT setting, Level 0's cutoff frequency is set to 500 Hz; Level 14's to 600 Hz and Level 13's to 700 Hz. The frequency goes up to 1900 Hz in the last level before the 'call back'. However, in my artistic performance, this shift was reversed (i.e. listeners would hear less and less of the high frequencies in the noise sounds while stepping into deeper layers of the forest).

Drum track

The drumming generated in this track uses ARE with frame drum sounds. It decreases in tempo and rhythmic complexity between the first outer and the last inner level. As seen in Fig. 5.12, these changes are introduced in stages. They are initialised at the start and retained until the end of each level.

The changes in rhythm from more to less complex patterns aim to help listeners gradually shift attention from more conscious (active) thinking characterised by higher brainwaves (e.g., beta) towards more

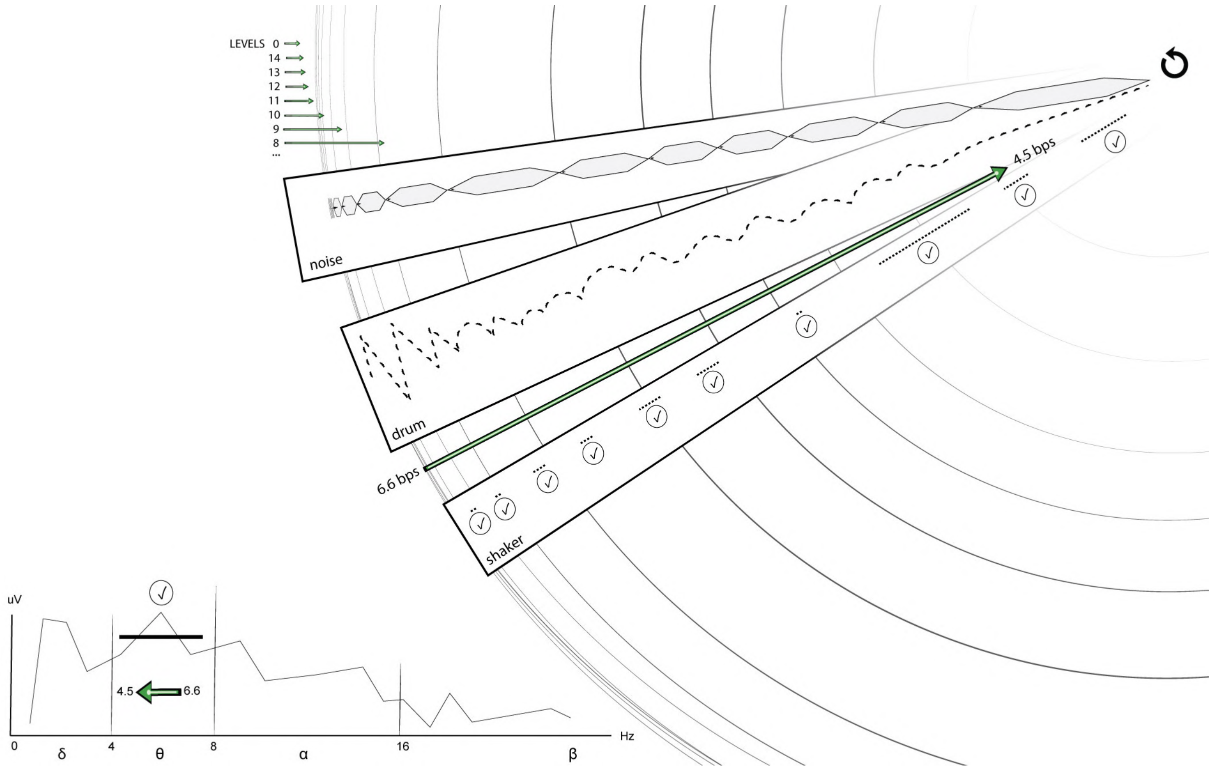

Figure 5.11: The figure on the left depicts a soundscape as a forest and indicates level durations and instrument activities in the tracks. The figure on the right visualises the neurofeedback protocol: when theta at Fz is above the threshold (black bold horizontal line), the protocol plays the shaker sounds, and when it is below the threshold, it mutes them.

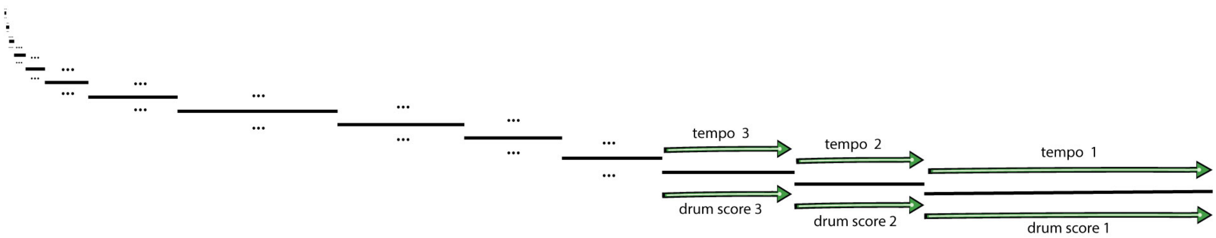

Figure 5.12: Shamanic soundscape levels with (horizontal) lines showing tempo and rhythmic complexity (drum score) remaining constant throughout each level.

subconscious (passive) thinking characterised by lower brainwaves (e.g., theta). On the other hand, the gradual decrease in tempo aims to help shift entrainment within the theta bandwidth from higher (6.6 Hz) to lower theta (4.5 Hz) brainwaves. To clarify, the decrease in rhythmic complexity aims to assist a wider shift (from beta to theta), while the decrease in tempo aims to assist a narrower shift (from high- to low-theta). Using these two changes in parallel, I hoped to be more effective in inducing and maintaining the SSC than I would if I used only one of these changes.

The frame drum sounds are 'dum', 'tak' and 'tek'. In hand-held style, 'dum' is the bass tone made when a fingertip or the thumb hits the middle of the drum (Fig. 5.13). 'Tak' is a higher frequency tone made when a fingertip hits the side of the drum. 'Tek', another higher frequency tone, is made when the drum's rim is hit with a fingertip. For naturally-sounding drumming, each sound was recorded multiple times using the mid-side stereo technique and then grouped into folders on the computer. The soundscape generator randomly picks samples from these folders every time a particular tone needs to be triggered.

Figure 5.13: Frame drum sounds ’dum’ (left), ’tak’ (middle) and ’tek’ (right).

To generate rhythms, each level is set up with arguments that first fill a bar of single or double paradiddles with ‘tak’ (0) and ‘tek’ (1), then some of these notes are replaced with ‘dum’ (2) and at last, selected notes are accented. See these three steps represented as arrays in the code and with traditional notation in Fig. 5.14.

```
[ 0, 1, 0, 1, 0, 1, 0, 0, 1, 0, 1, 0, 1, 0, 1, 1 ] // tak, tek
[ 2, 1, 0, 2, 0, 2, 0, 2, 1, 0, 2, 0, 2, 0, 2, 1 ] // dum
[ 1, 0, 0, 0, 1, 0, 0, 0, 1, 0, 0, 0, 1, 0, 0, 0 ] // accents
```

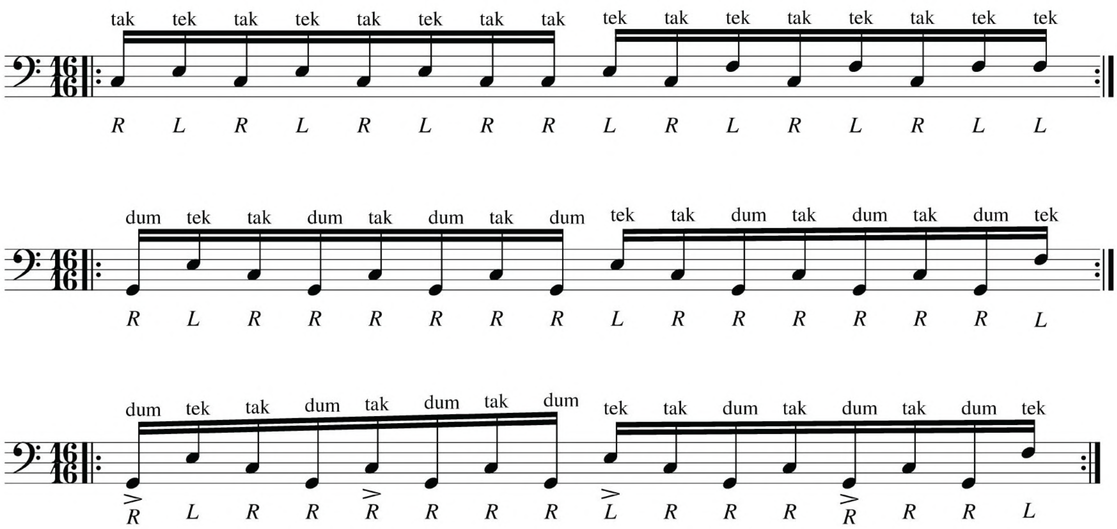

Figure 5.14: The generator’s three-step rhythm-making process in each level.

Adding the ‘dum’ notes and the accents uses the Bjorklund class by Olofsson (2010), which generates traditional musical rhythms based on Euclid Bjorklund’s algorithm (Toussaint, 2005). It works by computing the greatest common divisor of two given integers. For example, `Bjorklund(9, 16)` creates a rumba rhythm by placing nine notes distributed as evenly as possible in a 16-note length bar:

[1, 0, 1, 1, 0, 1, 0, 1, 0, 1, 1, 0, 1, 0, 1, 0]

I used the following code to set up the forests in the NFT setting (Section 5.4):

```
// [depth,bps,bpb,bjorkdum,bjorkaccent,shamanvol,windlpf]
~forest[0] = [0,4,16,0,0,0.2,500]; //level 0
~forest[1] = [1,6.6,16,7,4,0.2,600]; //level 14
~forest[2] = [2,6.5,16,5,3,0.2,700]; //level 13
~forest[3] = [3,6.4,16,3,4,0.2,800]; //level 12
~forest[4] = [4,6.3,16,2,8,0.2,900]; //level 11
~forest[5] = [5,6.1,16,1,8,0.2,1000]; //level 10
~forest[6] = [6,5.8,12,1,4,0.2,1200]; //level 9
~forest[7] = [7,5.6,8,1,0,0.2,1200]; //level 8
~forest[8] = [8,5.5,8,2,0,0.2,1300]; //level 7
~forest[9] = [9,5.4,8,4,0,0.2,1400]; //level 6
~forest[10] = [10,4.9,8,8,0,0.2,1500]; //level 5
~forest[11] = [11,4.8,8,8,1,0.2,1600]; //level 4
~forest[12] = [12,4.7,8,8,2,0.2,1700]; //level 3
~forest[13] = [13,4.6,8,8,4,0.2,1800]; //level 2
~forest[14] = [14,4.5,8,8,8,0.2,1900]; //level 1
~forest[15] = [16,2,4,8,3,0.2,700]; //call back
~forest[16] = [17,2,4,8,3,0.0,400]; //level 0 (drums quiet)
```

To clarify, I will explain in detail the array of Level 14 (`~forest[1] = [1,6.6,16,7,4,0.2,600]`). This array first defines this level's depth as `1`, referring to the first outer layer of the forest, and its tempo as `6.6` BPS. Value `16` creates a paradiddle with 16 beats that has `7` 'dum' notes and `4` accents. Towards the end of the array, the overall volume of the frame drumming is set to `0.2` (range=0.0-1.0) and finally, the last value, `600`, sets the low-pass filter's cut-off frequency in the noise track's long sustained sound.

In the above example, when the number of 'dum' notes equals the number of beats in the bar (from Level 5 onwards), the paradiddles are replaced with monotone patterns consisting of 'dum' only. See score of Level 5 in arrays and traditional notation in Fig. 5.15 below:

```
[ 0, 1, 0, 0, 1, 0, 1, 1 ]
[ 2, 2, 2, 2, 2, 2, 2, 2 ] // tak & tek (0,1) replaced by dum (2)
[ 0, 0, 0, 0, 0, 0, 0, 0 ] // no accents
```

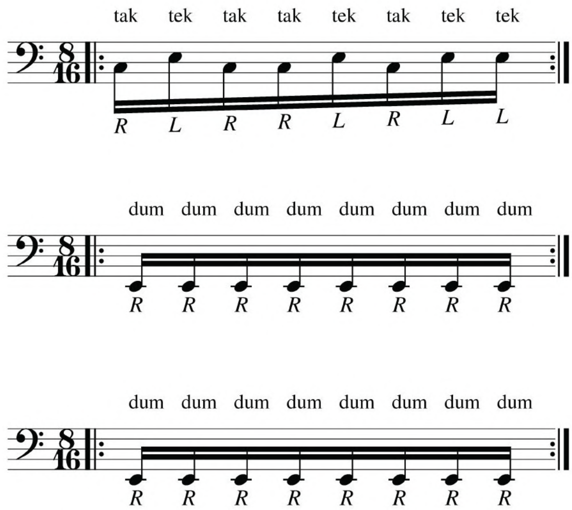

Figure 5.15: The generator's three-step rhythm-making process for Level 5.

Shaker track for the neurofeedback protocol

In this track, short synthesised shaker sounds are played when theta energy at Fz is above a threshold and muted when this energy is below this threshold. These sounds are immediate neurofeedback indicators, the reward sounds of the neurofeedback protocol (Fig. 5.16). Rewarding increased theta was inspired by research highlighting this increase during concentrative meditation (Baijal and Srinivasan, 2009), receptive meditation (Lagopoulos et al., 2009; Tarrant, 2017), alpha-theta NFT (Gruzelier, 2008; Collura, 2017, p.134), and while listening to repetitive music (Strong, 1998; Maas and Strubelt, 2003; Fachner, 2006b; 2006a; Jovanov and Maxfield, 2011; Becker, 2012; Will and Turow, 2012). I chose location Fz based on the thoughtless awareness NeuroMeditation protocol outlined in Section 3.3.2.

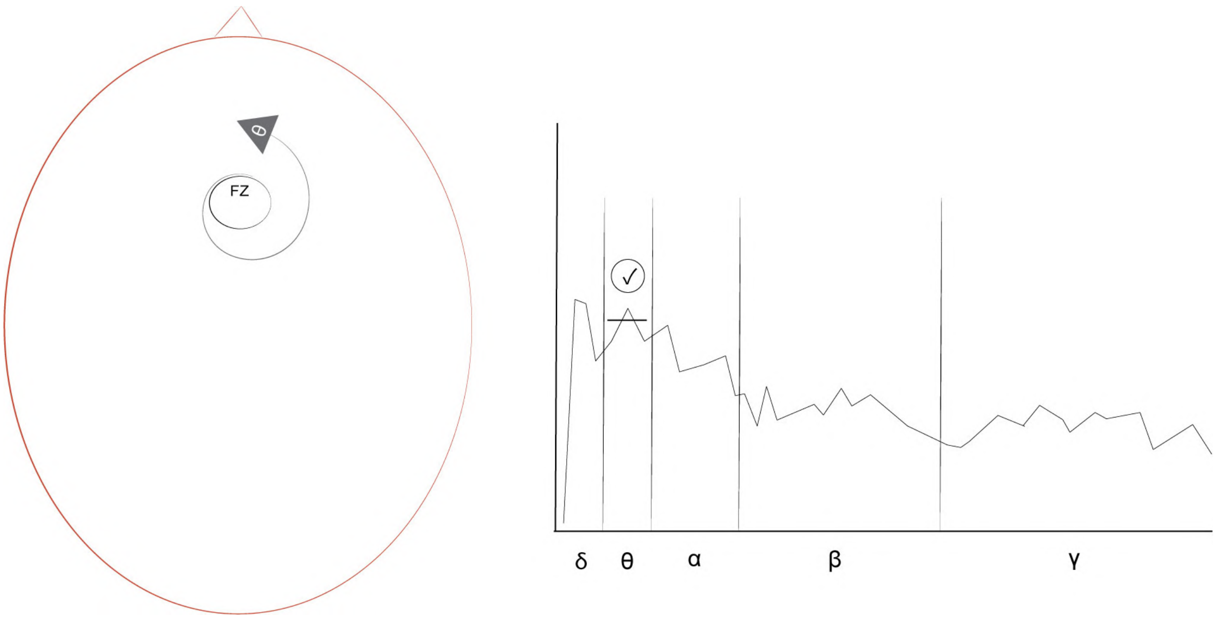

Figure 5.16: The electrode location of BCMI-2's neurofeedback protocol (left) and a spectral plot (right) showing the application of one indicator at Fz.

Table 5.1 summarises the main aspects of the three tracks:

Table 5.1: The soundscapes' noise, drum and shaker track summary.

	noise	drum	shaker
type	noises	frame drum	shaker
source	synthesised	audio sample	synthesised
trigger	controlled	semi-controlled	controlled
BCI mapping	no	no	yes
entrainment	change in pitch	change in tempo and rhythm	neurofeedback

5.3.4 Conclusion

Research and project objectives

This project addressed RO2 — it developed the mapping and control parameter steps of BCMI-2 based on insights from the BCMI-1 project, my literature review findings, the feedback I received from public demonstrations and the technical aspects of the OpenBCI–SuperCollider Interface. The project's primary outcome is a novel soundscape generator that can be effortlessly linked to the OpenBCI-SuperCollider Interface and possibly to other BCI systems using OSC. The project addressed all its objectives successfully.

The Shamanic Soundscape Generator

- Effortlessly acquires classified EEG in the form of global variables from the OpenBCI-SuperCollider Interface, also running in SuperCollider.
- Provides customisable options for mapping this classified signal to sound control parameters.[7]
- Generates soundscapes with customisable ARE, of which the neurofeedback reward sound is an integral element. We can customise the length of the soundscape and its levels, the tempo and rhythmic variations in each level, and the sounds that are triggered (for example we can use different drum samples).

New objectives

To improve this software, I will

- write code that creates smoother transitions between levels
- add extra drum tracks to experiment with polyrhythmic patterns
- add accumulative feedback to the neurofeedback protocol (based on the BCMI-1 neurogame)

[7] While the neurofeedback protocol in this BCMI-2 project rewarded increased theta at Fz with a synthesised shaker sound, several aspects of this sound could be altered with textual programming or alternative sounds be synthesised or played back from audio samples instead. With little changes to the code, we could even map the classified data to other aspects of the soundscape, e.g. the parameters of the ARE or the continuous noise sound textures.

- incorporate the use of the Ambisonic Toolkit as an alternative to the current surround spatialisation method to help control the sound field more precisely (ambisonictoolkit.net)

Next, in Sections 5.4 and 5.5, I outline how I tested BCMI-2 in NFT and artistic performance settings.

5.4 NFT Setting

5.4.1 Project overview

This project addressed RO3 — it demonstrated BCMI-2's suitability to support meditation practices in an NFT setting. After establishing the system's stability in tests that used my own brainwaves, I recruited two participants to gain experience using the system in supporting others interested in deepening meditation. The type of meditation practised was shamanic journeying (Section 3.4.3) with the two training methods (ARE and a neurofeedback protocol) as outlined in the previous section on the Shamanic Soundscape Generator software. After three sessions with each participant, I analysed the data gathered in their questionnaires, BCMI data files and screencasts. While they did not experience a breakthrough into the SSC, one participant made progress in deepening her meditation and expressed interest in a follow-up study. The system was stable throughout the project and has clarified new objectives that could make it more efficient. In addition to addressing RO3, the project also produced digital audio that was released on the internet, featuring soundscapes generated with the system.

Project time span: September 2019—February 2020

Supporting materials:

- YouTube Video Playlist | Audio-video archive of the six NFT sessions described below and a short video introducing the environment where the sessions took place.
- *Shamanic Soundscape - Neurofeedback Training Sessions* | A digital audio release with stereo files on Bandcamp for online streaming. The release contains three soundscapes, two of which were generated using BCMI-2 during the sessions described below and one that was created during a session in which I tested the system.

5.4.2 Goals

To address RO3 — to test BCMI-2's suitability to support meditation practices in an NFT setting — the goal of this project was to prepare and run NFT sessions using the system and then analyse the archived data. Therefore, the objectives of this research were to

- find participants and prepare the practical aspects of the sessions (e.g. the environment and questionnaires)
- prepare the BCMI-2 system to provide entrainment and archive BCMI data files for later analysis
- prepare other software and hardware tools for archiving screencasts

- prepare participants and run the sessions
- analyse the archived data in the questionnaires, the BCMI data files and the screencasts

I addressed these objectives using insights from the literature review (Sections 3.2, 3.3 and 3.4) and insights from my own NFT sessions using the system.

5.4.3 Design and development

5.4.3.1 The set and setting

Born out of psychedelic research (Leary, Litwin and Metzner, 1963; Zinberg, 1984; Hartogsohn, 2017; Carhart-Harris et al., 2018), the concepts of 'set and setting' in meditation practices is also relevant to my research. How my soundscapes affect listeners depends on a variety of factors. These factors include the emotional significance of the circumstances in which the listening takes place (setting), the cultural and musical background of the listener (set), the mental state of the listener (set) and the listener's intentions (set) (Sloboda, 1985; Trost and Vuilleumier, 2013; Will, 2017). Without clear intentions, it can be challenging to deepen one's meditation. A clear intention can help a listener stay focused and maintain the self-compassionate, non-reactive attitude that is crucial for progress (Shapiro, Siegel and Neff, 2018). When preparing the sessions, I tried to consider all these factors.

Two volunteers, B and M, from Han Chinese tradition in their 50s, each participated in three sessions (n=2, trials=3). I held the sessions in a small room with only essential furniture and technology in a quiet, undisturbed house. To help them become immersed in the specific type of meditation (the shamanic journey), I attempted to create a sense of ritual and sacredness by smudging a small amount of sage in the room before the sessions and by burning a candle in front of them throughout the sessions. I also offered blankets for comfort. All sessions took place a couple of days apart to help 'learnt gains to be reinforced and retained' (Collura, 2017, p.198). During a session, I sat in front of them, instead of beside or behind the participant, to help increase their comfort. To make sure their meditation was as undisturbed as possible, I set the laptop screen visualising their brainwaves out of their sight and took notes quietly with a pencil on paper instead of typing on the much louder laptop keyboard.

Shamanic journeys in core shamanic practices typically last between 15 and 30 minutes. Pilch, based on Dr Felicitas Goodman's research (Goodman and Nauwald, 2003), reinforces the 15-minute minimum:

> ... shaking a rattle (or beating a drum) approximately 220 times a minute [4 Hz] for a 15-minute period provides the optimal sensory stimulus to the nervous system for inducing a trance ... (Pilch, 2006, p.44)

In music therapy, Perret writes about a similar minimum length required for opening deeper levels in clients:

> Depending on the musician's state, I would probably insist on her playing for at least five to fifteen minutes. There may be exceptions of course. Usually, though, it is about this length of time that is necessary for the player to get over her initial inhibitions, to find an opening to deeper levels and to let herself be carried away so that the musical expression will truly reflect what is happening inside.

> The inner level is not limited to our emotions but may engage any aspect within us which is more or less conscious, for instance the collective unconscious, energy phenomena and spirituality. (Perret, 2005, p.143)

This minimum 15-minute requirement to change the state of mind is also supported by my experiences with shamanic journeying using the BCMI-2 system, as well as drumming, practising breath-work and running outside. Therefore, to give participants enough time to induce and maintain the SSC, the length of time for the soundscape generated in each NFT session was set to be 30 minutes long.

Preparing the set — my participant's mindsets regarding the study's goals and the methods used to help achieve these goals — required careful considerations. For example, how much detail should participants be given about shamanism, the proposed advantage of ARE over more monotonous sonic driving and the neurofeedback protocol? When I approached B and M a couple of weeks before the sessions, I told them about my research and asked whether they could help test my new tool's suitability to support meditation. After confirming their participation, I told them not to consume food for a couple of hours before the sessions to comply with preparations for shamanic journeys and told them that I would provide more information about the study in their pre-listening questionnaires.[8]

5.4.3.2 The sessions

Parts of a session:

- Part I – Pre-Listening
- Part II – Listening
- Part III – Post-Listening

In **Part I – Pre-Listening**, I used a short questionnaire to introduce the study and to gather data. The questionnaire introduced how repetitive drumming has been used in shamanic traditions to induce the SSC; however, it did not specifically explain how the combination of ARE and a neurofeedback protocol aims to help induce and maintain this SSC. Then, it inquired about participants' research-related conditions and experiences, including brain-related medical conditions, left/right-handedness, previous experience with BCI, meditation and shamanic journeying, musical preferences and level of musical skill. The questionnaire also asked about their alcohol, drug and food consumption within a few hours of the session and whether they felt tired or focused. After they filled in the questionnaire, I asked them to relax and focus on the rhythmic patterns in the 30-minute soundscape as much as possible, more by 'feeling' than through 'analytically thinking'. I explained that BCMI-2 maps parts of their brain signals to parts of the soundscape but did not specifically explain that the neurofeedback reward, the shaker sounds, are only played when their theta brainwaves at Fz go above a certain threshold – a threshold I set manually.[9]

---

8 I discussed preparation for shamanic journeys with two admins from different shamanic groups on Facebook in November 2019 via private messages. One admin aligned herself with traditional shamanism, the other with core shamanism.

9 The questionnaires and data gathered can be found in Appendix 3.

In **Part II - Listening**, I recorded two files:

- an audio-video screencast file (mp4) and
- the BCMI data file (txt).

After I set up participants with eight EEGs using the Greentek Gelfree cap, I began recording a screencast using ScreenFlow (Telestream, 2017). After that, I lowered the electrode impedances by adding more saline water to the electrodes in the cap. I aimed to keep impedances below 10 kOhms. Once I could not lower the impedances further, I began feature extraction with the FFT plot GUI of the OpenBCI-SuperCollider Interface. To adjust the neurofeedback threshold manually, I executed code in SuperCollider's editor. Once a threshold seemed usable, I started the soundscape at Level 0 (outside of the forest) and began recording the BCMI data file. While listening to the sustained noise of Level 0, I prepared myself and the participants for the journey. I reminded them to keep their eyes closed while listening to the drumming and then moved the soundscape to the first outer layer of the forest, Level 14, where the entrainment began. Fig. 5.17.

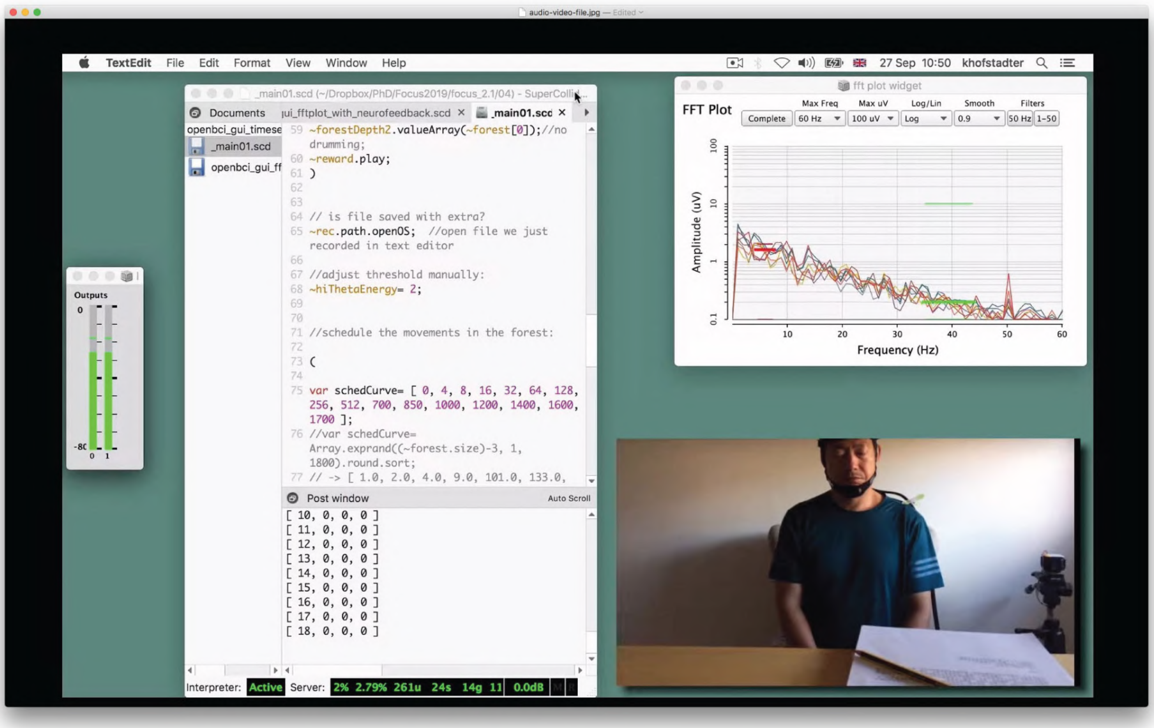

Figure 5.17: Snapshot of an NFT session's screencast showing three SuperCollider windows (from left: audio volume meter, IDE with textual programming/post window and FFT plot) and one camera window.

Throughout the soundscape, I tried to be as helpful as possible by sitting mindfully with a straight spine while searching the screen for artefacts and interesting changes in the FFT plot. I took notes quietly with a pencil in a physical notebook. In every session, I was hoping to gradually hear an increasing number of shaker sounds and see a shift from strong alpha to strong theta brainwaves, indicating a breakthrough (see Sections 3.2 and 3.3 for more information on breakthroughs).

After participants reached the middle of the forest, a 'call back' sent them back to the outside of the forest, where the soundscape finished. I stopped recording the BCMI data file, checked the electrode impedance and then stopped recording the screencast. During the **Part III - Post-Listening stage**, I assessed participants' experiences in the forest by asking them to fill in a short questionnaire and to recall visual images, if they had any, by trying to draw them on paper. Then, about a week later, in **Part IV - Follow-up**, I asked for further feedback regarding the most pleasant and unpleasant parts of the sessions, the comfortableness of the environment, the effectiveness of the drumming in helping produce visions and the effectiveness of drawing for remembering visions as well as whether they were interested in a follow-up study. Their feedback was positive and constructive, and they were interested in continuing the study.[10]

5.4.4 Deployment

5.4.4.1 Analysis

My analysis used (1) plots of the BCMI data files, (2) questionnaire data and (3) screencasts.

Participant B

The classified data (theta at Fz) from **session B1** could not be considered a reliable input for the neurofeedback protocol or later off-line analysis as it was affected by numerous muscle movements and touching of the EEG cap (Fig. 5.18). Unfortunately, B did not report visual imagery either. However, the session helped highlight two issues:

- a tired participant cannot offer the focus required for successful meditation
- participants need more clarification on the significant effects that physical movements have on EEGs

In **session B2**, the participant, being less tired than in the previous session, produced clearer EEG and some abstract visions:

> Irregular images emerging, like a dream... Two concentric circles, outer one representing the field of view, inner one the stranger's face appearing in front and from the left in the dream. The image appeared once.

B remembered these visions to be around three-quarters into the soundscape, which is, unfortunately, when we also see many artefacts in Fig. 5.18. Therefore, it is not possible to relate this vision to the quantitative data. Furthermore, although his overall EEG was much clearer than in the previous session, still numerous artefacts interfered with the neurofeedback protocol (i.e. often movements triggered the shaker sounds instead of strong theta waves). Another issue in this session was that the neurofeedback threshold was not adjusted effectively at the start — it was too high throughout the session. Therefore, most rewards were likely triggered by artefacts instead of by strong theta brainwaves.[11]

---

[10] While the six BCMI data files from the sessions are not shared publicly, as they contain participants' raw EEG data, the screencasts are unlisted videos on YouTube. We can find the summary of the questionnaires in Appendix 3.

[11] In Fig. 5.18, the red line is slightly higher in the middle plot than in the two other plots when compared to the theta signal.

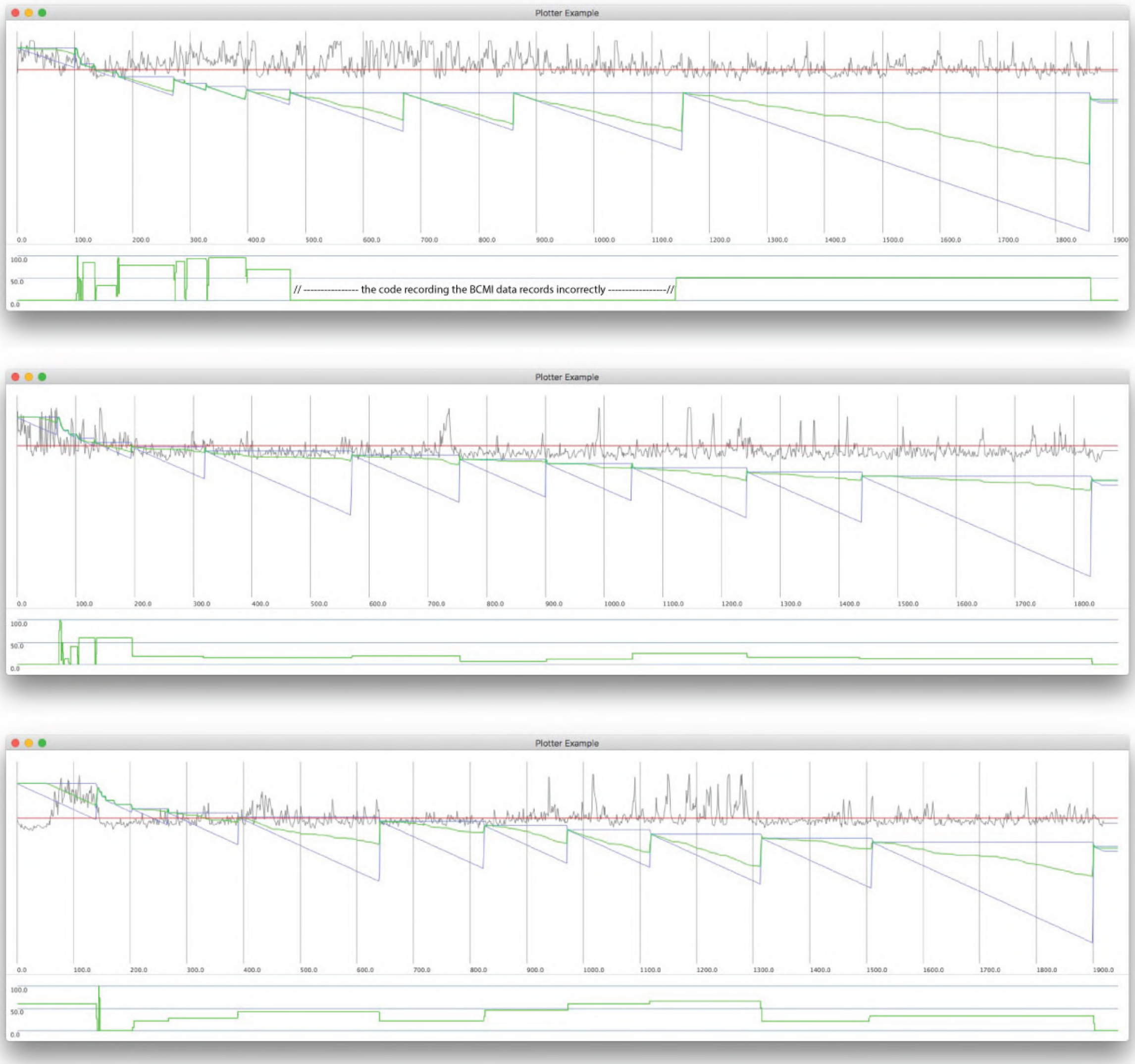

Figure 5.18: BCMI data plots from sessions B1 (top), B2 (middle) and B3 (bottom). The top part of each plot shows (1) theta median at Fz (wiggly grey lines), (2) neurofeedback threshold (red horizontal lines), (3) soundscape level durations (blue triangles) and (4) averaged neurofeedback success rates for each level (green lines in the blue triangles). The closer the green line gets to the bottom right corner of the blue triangle, the higher the neurofeedback success rate for that level. The bottom parts of the plots visualise the success rates again, with higher green steps indicating higher success rates.

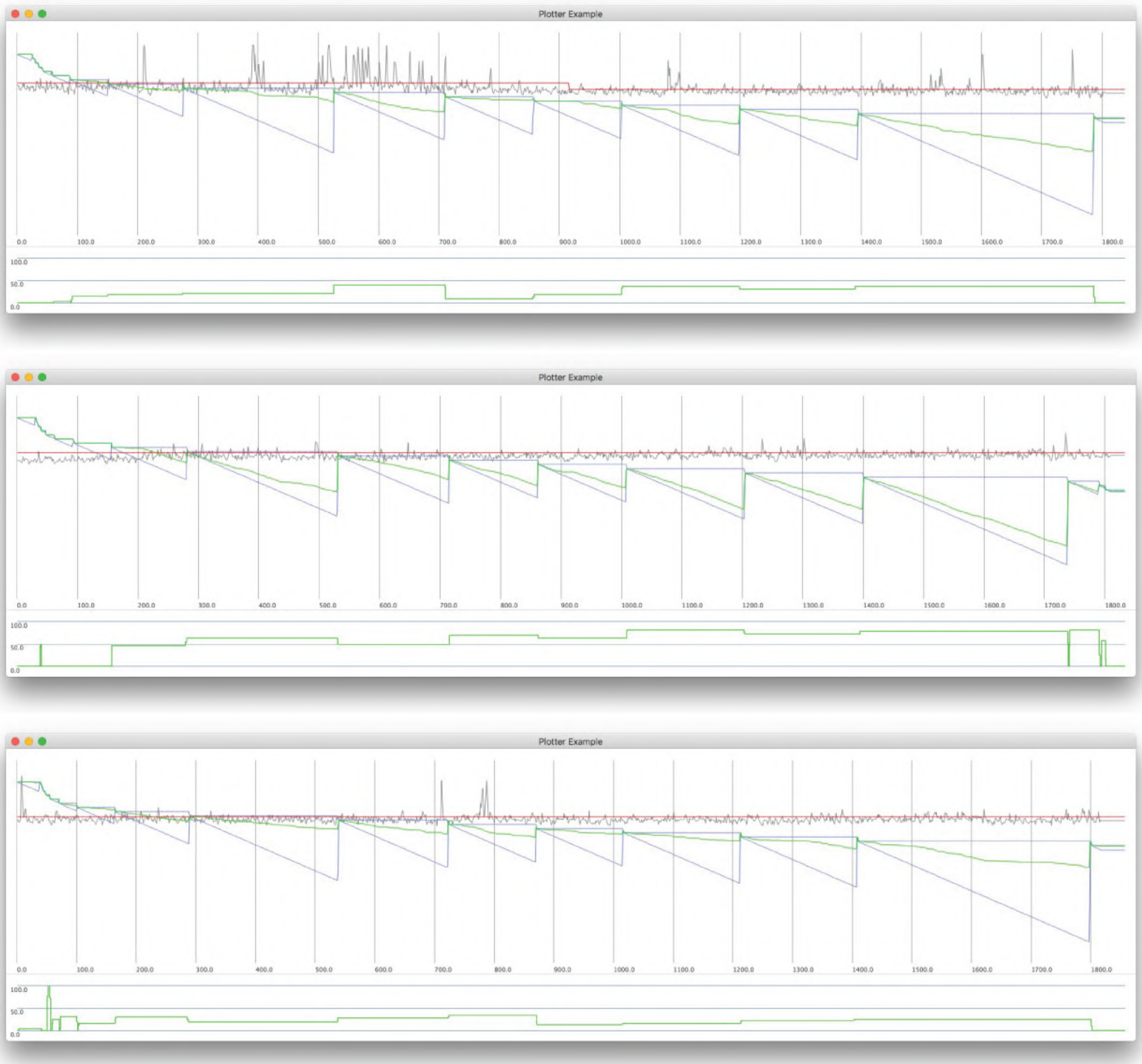

Figure 5.19: BCMI data plots from sessions M1 (top), M2 (middle) and M3 (bottom). See previous figure for more detail.

In **session B3**, his first comment on his visions was that 'there were no special images in [his] subconscious'. However, his later statement was quite precise, which may indicate that his visions in this session were actually more concrete than in the previous session:

> I saw a foreigner (translator's note: Caucasian male), around 40, with a black beard. He looked like he was selling snacks/deli.

On average, the EEG in this session is clearer than in his two earlier sessions. Although polluted by some artefacts, the bottom plot in Fig. 5.18 shows that his theta brainwaves became stronger in the final levels of the soundscape. Unfortunately, his information sheet does not indicate the level in which he experienced the above vision.

Participant M

There were two issues encountered in **session M1**. First, strong eye movements contaminated the EEG for the first third of the recording, which (based on the answers in the questionnaire) may have been caused by nervousness or difficulties with 'feeling' the drumming and pausing an internal dialogue. Second, the neurofeedback threshold was not adjusted effectively until the middle of the soundscape. (These two issues can be seen in the top plot of Fig. 5.19). M found the middle of the soundscape to be the easiest to focus on, where she also experienced several visions:

> I saw another me in the clouds. ... I saw the pores on the surface of my skin. ... I felt golden light in front and to the right of my eyes.

Session M2 was M's most successful session for the following reasons. The quality of her EEG was clear and the neurofeedback success rate high throughout the session (Fig. 5.19). She also experienced visual imagery, remembered as follows:

> In the middle section, there was a very big meadow in the shape of a funnel. Many people, including the five people in our family, were playing on it.

In **session M3**, the quality of her EEG was clear most of the time and she also experienced visual imagery. However, the neurofeedback success rate was lower than in the previous sessions. Her visions are described below:

> In about the last one-third of time, there was a hole (in between my eyes and nose) in an irregular shape. Through the hole, there was a green meadow. Many people were playing on it.

Summary of analysis

There were two signs of progress observed in B's training. Session by session, his EEG and his visions became clearer. M's EEG, on average, was clear, and she produced visual imagery in all her sessions. When comparing B's sessions with M's sessions regarding (1) clarity of the EEG, (2) number and clarity of the visions produced and (3) neurofeedback success rates, I consider M's sessions more productive. I could only link the correlations found between (1) the BCMI data files, (2) the questionnaire data and (3) M's better performance to differences in their musical preferences and their level of difficulty with pausing internal dialogues during the listening parts. While B's musical preference is folk music, M's is classical music. While B described pausing his internal dialogue as 'easy' in two sessions and 'very easy' in one session, M described this task as 'hard' in all of her sessions. M's preference for classical music may indicate her ability to focus better on more complex musical patterns, which may be the reason for her better performance. Also, the fact that M's visions were clearer and more frequent than B's, despite her finding it more difficult to pause her internal dialogue than B, may suggest that she took the study more seriously than he did. Overall, my feeling is that it was her commitment that helped her perform better. However, I can only hypothesise. Unfortunately, none of the six recordings suggest breakthroughs. However, as there was progress with both participants, future sessions with them could produce clearer EEGs, more visual imagery and breakthroughs. Due to the COVID-19 pandemic, the follow-up study with M was cancelled in January 2020 and is still waiting to be rescheduled.

5.4.4.2 Audio release

A creative output of this project is the digital audio release on the internet titled *Shamanic Soundscape - Neurofeedback Training Sessions* (Hofstädter, 2019f) (Fig. 5.20). It contains three mixed and mastered soundscapes: two that were generated in the sessions with B and M and one that was generated during my training.

5.4.5 Conclusion

Research and project objectives

By addressing all its objectives, the project addressed RO3 — it demonstrated BCMI-2's suitability to support meditation practices in NFT settings. The system was stable in all six sessions. During the sessions, it provided entrainment with ARE and a neurofeedback protocol as well as archived a BCMI data file for later analysis. The plotting of this BCMI data file, together with questionnaire data and screencasts, helped produce an analysis of the sessions. The on-line sessions and the off-line analysis provided valuable insights on how the system itself and its application in NFT settings can be further improved and eventually used for studies with scientific rigour (e.g. to test different ARE and neurofeedback protocol parameters to support different meditation practices).

New objectives

Despite the successes mentioned earlier, I could not identify signs of breakthroughs in the participants' EEGs or feedback forms. Although visual imagery can indicate the start of a mental shift, without precise information on when exactly these visions occurred, it is impossible to establish the causal relationships between the vision, the classified EEG (increased theta) and the rhythmic patterns of the soundscape. To address this shortcoming, BCMI-2 needs an additional sensor that participants can use to signal when they see a vision. This could be a simple binary sensor (e.g. an on/off button that they hold down when a vision occurs and release when there are no visions). I could also add a more sophisticated sensor with a linear transfer function (e.g. an accelerator with which participants could indicate the intensity

Figure 5.20: Cover art for *Shamanic Soundscape - Neurofeedback Training Sessions* (2019).

of the vision by moving the physical position of one of their hands higher or lower). To connect one of these sensors, one could follow the analogue pulse sensor guide by OpenBCI (2020) and then create the appropriate scaling in the code of the OpenBCI-SuperCollider Interface.

In forthcoming studies, I will increase the number of participants and make sure that participants with (1) no meditation experience, (2) moderate experience and (3) advanced experience are represented in equal proportions. Furthermore, it will be essential to inform participants about how crucial it is to avoid physical movements throughout the recording to produce usable EEG data. I could share this information with them in a short video while setting up the EEG caps and adjusting electrode impedances. This video could also serve as a recap or extension of the textual introduction already given to participants. The video should be produced with appropriate audio-visual material that, while informing the participant, also prepares the meditation (e.g. by using a calming voice and soothing visuals and sounds). Additionally, items in the questionnaire need to be more specific. For instance, instead of the closed tired/focused question, participants should be able to indicate this condition on a scale of 0 (tired) - 100 (focused). Finally, my unfinished Matlab code requires further development in order to verify the SuperCollider plotting of the BCMI data files. Matlab could also help with artefact removal and the implementation of additional EEG analysis tools currently unavailable in the OpenBCI-SuperCollider Interface (e.g. EEG topography highlighting synchronised brainwave characteristics, perhaps in real time).

Next, Section 5.5 outlines BCMI-2's suitability for artistic performance settings with additional surround sound, acoustic drumming and sonification of brainwave synchronisation, all to help increase the engagement of my audience.

5.5 Performance Setting

5.5.1 Project overview

This project addressed RO3 — it demonstrated BCMI-2's suitability to support meditation practices in artistic performance settings. After establishing the system's stability in tests with my own and others' brainwaves (Section 5.4), the next step — as a natural progression — was to demonstrate its ability-enhancing potential to an audience. Following the guidance of key BCMI researchers (Williams and Miranda, 2018), I enhanced the system used in the previous NFT setting with additional functions to help provide a musically engaging experience. These functions included acoustic drumming and mapping theta brainwave coherences to surround sound spatialisation of abstract sound textures. Although my own meditation during my 2019 Cambridge Festival of Ideas performance did not produce a breakthrough, the system was stable, and feedback from the audience was insightful. The project helped create works of art (audio and video), highlighted how the system can be improved for artistic performances and raised people's interest in participating and researchers' interest in collaborating on upcoming projects.

Project time span: October 2019—February 2020

Supporting materials:

- Cambridge Festival of Ideas 2019 Performance Video 1 | A video collage of a screencast and two additional camera shots archiving my performance at the 2019 Cambridge Festival of Ideas.
- Cambridge Festival of Ideas 2019 Performance Video 2 | An alternative version of the above video, with additional binaural beats. The start of the video provides annotations clarifying the neurofeedback protocol used on theta at Fz.
- *Shamanic Soundscape - Level Two* | A digital audio release with stereo files on Bandcamp for online streaming and in a physical Digipak for CD players, with additional surround formats for downloading. The release contains three soundscapes: one that was generated using BCMI-2 in rehearsal, one that was generated in performance and an alternative version of the latter with binaural beats added in post-production.
- *Shamanic Soundscape - Jester (Quad Mix)* | Surround version of a track from the above audio release, published for online streaming.

5.5.2 Goals

To address RO3 — to test BCMI-2's suitability to support meditation practices in artistic performance settings — the goal of this project was to prepare and perform with the system at a public event, analyse the archived data and produce some creative outputs. Therefore the objectives of this project included the following:

- find a relevant venue
- organise technical support for setup and soundcheck
- book sufficient time for technical setup and rehearsals in the room
- prepare the BCMI-2 system for performance and for archiving the BCMI data file
- prepare other software and hardware tools to archive audio and video, including different camera shots, a screencast, microphones and surround sound spatialisation
- run the event
- analyse the BCMI data file in SuperCollider with the archived screencast
- produce creative outputs (e.g. audio releases and videos archiving the performance) to help raise public and academic interest in my research for upcoming projects

These objectives were informed by technical aspects of BCMI-2; literature review in Chapter 3; insights from the previous NFT setting (Section 5.4); technical and aesthetic aspects of computer music; emerging questions and methods and progress with using the system to deepen my meditation.

5.5.3 Design and development

Shortly after the NFT sessions with B and M, I applied to present my research and perform with the BCMI-2 system it developed at the 2019 Cambridge Festival of Ideas (Hofstädter, 2019d).

> The Festival of Ideas is a University of Cambridge public engagement initiative that celebrates the arts, humanities and social sciences by showcasing a diverse mix of inspirational talks, performances, films, exhibitions and other creative displays. (University of Cambridge, 2019)

After my application was accepted, I began preparing for the practical, technical and aesthetic aspects of the event. The set and setting (Section 5.4.3.1) for this performance required careful consideration (Fig. 5.21). As it was a highly technical performance, I made sure I could set up the system the night before and rehearse at least once with support for soundchecks. I began the event with a 20-minute presentation outlining the research. Then, I prepared the audience for the performance. I invited them to either meditate with their eyes closed or observe correlations between the soundscape and the visualised EEG during the performance.

Figure 5.21: Photos contrasting the NFT (left) and the performance (right) settings.

5.5.3.1 New tracks and surround sound

As Williams and Miranda (2018) highlight, BCMI must not only respond to meaningful brainwave information, but the response needs to be musically engaging as well. Therefore, to help increase my and my audience's engagement during the performance, I extended the soundscape with three new tracks — the 'live drum', the 'electro-acoustic drum effects' and the'counter' track — and utilised quadraphonic sound (4.0 surround sound) for spatialisation (Fig. 5.22).

The live drum track contains my improvisation on an acoustic frame drum. Its primary function was to continuously interpret my meditation progress and secondary to provide a sound source to be transformed using effects and then spatialised with theta coherence measurements in real time. To clarify, in addition to the neurofeedback protocol rewarding increased theta on Fz with shaker sounds (as in the previous NFT setting), in this performance, BCMI-2 also mapped other classified signals — theta brainwave coherences — to other sounds. More specifically, it mapped intra- and cross-hemispheric theta amplitude coherence

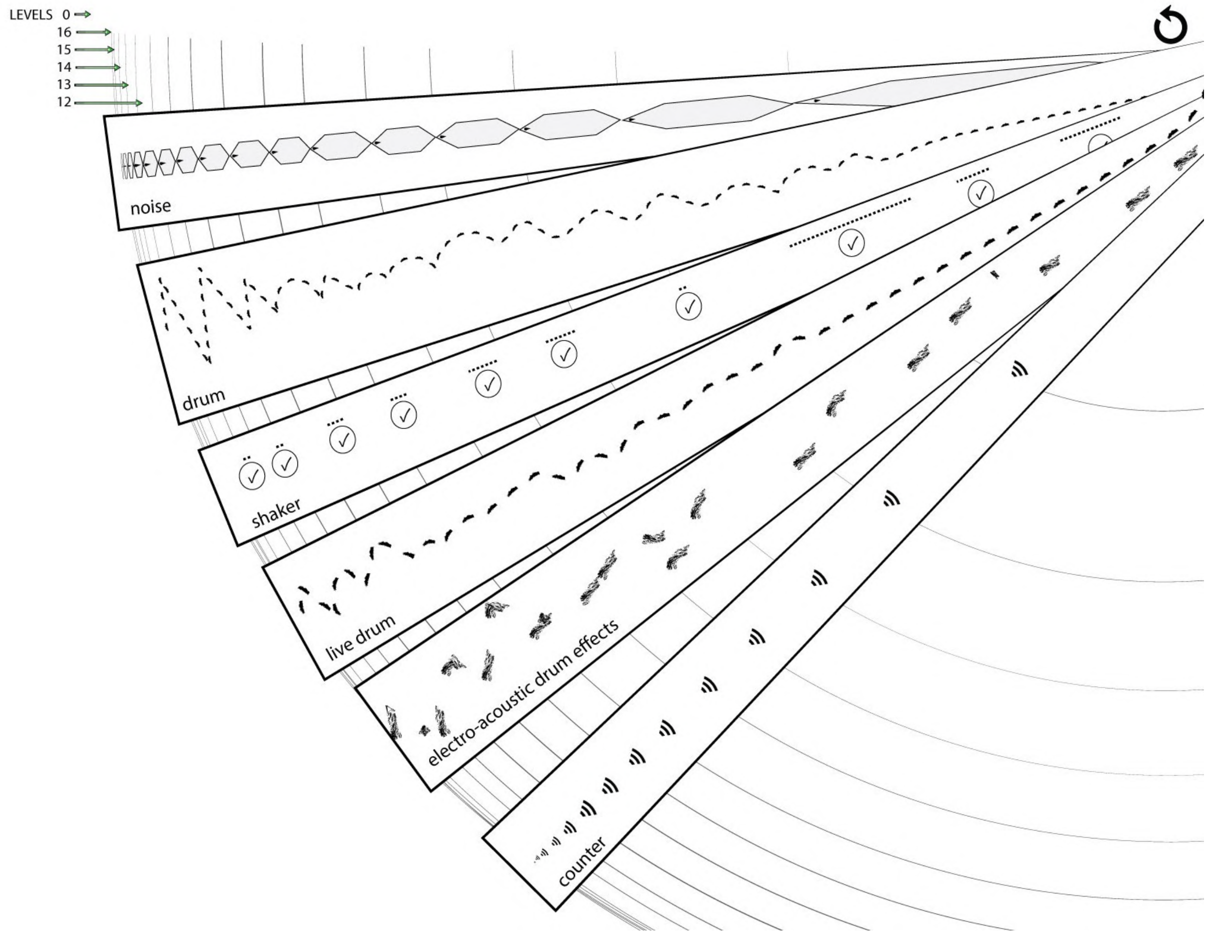

Figure 5.22: The visual interpretation of the performance's soundscape (forest) with six tracks.

signals to surround sound spatialisation parameters of the transformed acoustic drum sounds.[12]

Not only to interpret the progress of my meditation to the audience but also to support all our shifts into an SSC, I often juxtaposed the rhythmic patterns generated by BCMI-2 with patterns made with my fingers on the frame drum. We can hear an example of this juxtaposition when I overlay the computer-generated four-by-four patterns with improvised triplets on the acoustic drum from 10:20 minutes onwards in *Jester*. My aim with this juxtaposition was to experiment with polyrhythms that have been linked to inducing ASC in African drumming (Maas and Strubelt, 2003).

The BCMI-2 system distributed the sound of the noise, the (computer-generated) drum, the live drum and the counter track equally across all four speakers throughout the performance. However, the sounds mapped to brain signals were all in motion. The shaker sounds moved in a steady clockwise circular motion around the audience, but the electro-acoustic drum effects moved in a more unpredictable way (Figs. 5.23, 5.24).

[12] For this coherence sonification, the code of BCMI-2 was updated with additional feature extraction, classification, mapping and control parameter functions. As discussed earlier in Section 5.2, I have updated the code extracting coherence features since this performance, and now, instead of extracting amplitude coherence, the code extracts phase coherence. This function can be found in the OpenBCI-SuperCollider Interface's `openbci_gui_fftplot_with_neurofeedback-8ch+coherence.scd` file. We can find the code for the surround spatialisation in the Shamanic Soundscape Generator's SuperCollider files.

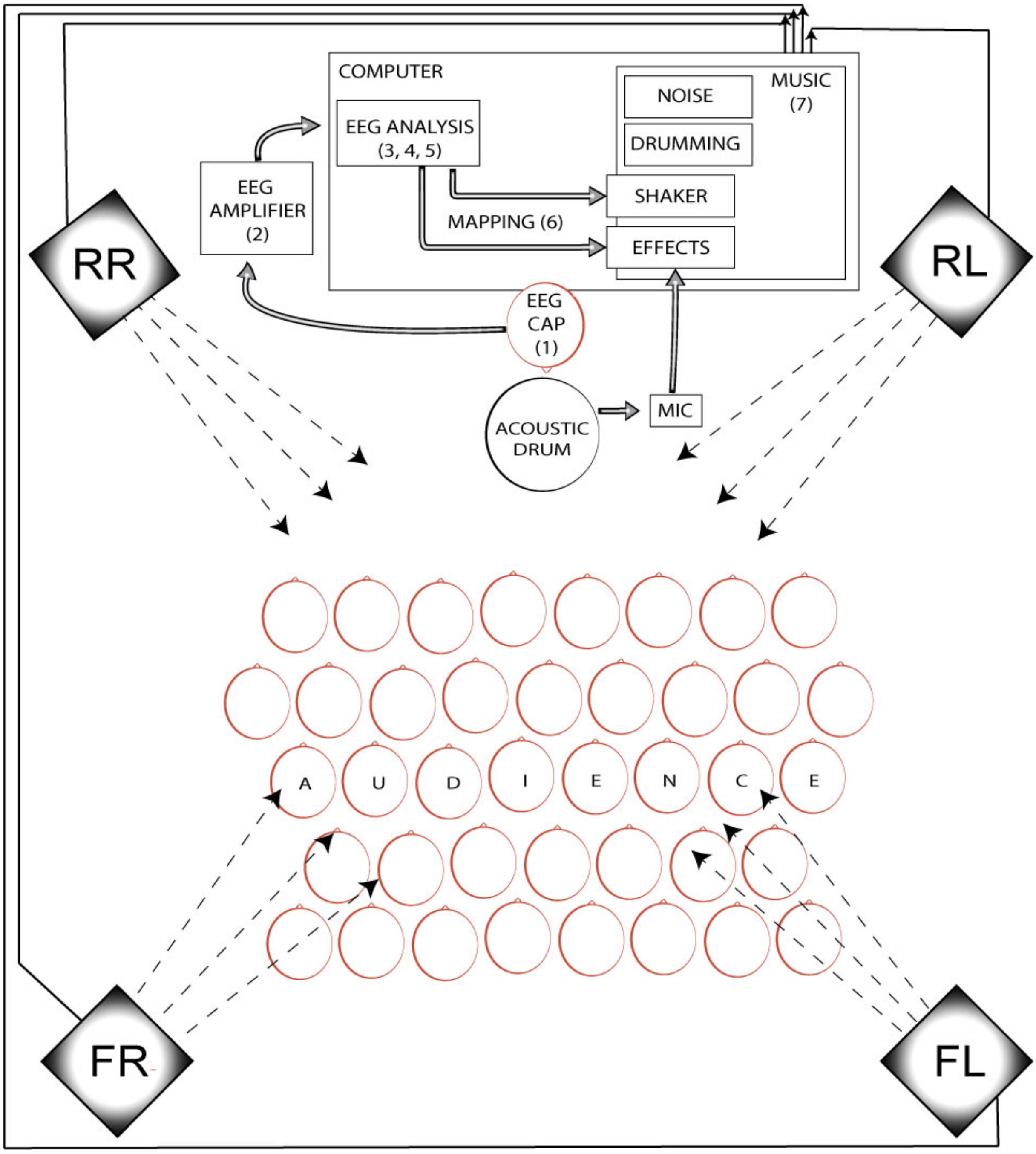

Figure 5.23: The performance's speaker setting and BCMI steps – (1) electrical fields are picked up with the EEG cap; (2) signal amplification and A/D conversion take place on the OpenBCI board; (3) noise reduction cleans user- and system-related artefacts; (4) feature extraction occurs using FFT and coherence tools; (5) meditation-related theta brainwave energy at Fz and intra- and cross-hemispheric theta amplitude coherence measurements are classified via EEG from brain areas F4, P3 and P4; (6-7) the classified signals are mapped to the shaker sound and spatialisation (effects) parameters. Note: speaker arrangement is from the performer's perspective – front left (FL), front right (FR), rear right (RR) and rear left (RL). A small triangle on the EEG cap indicates the performer's (my) nose.

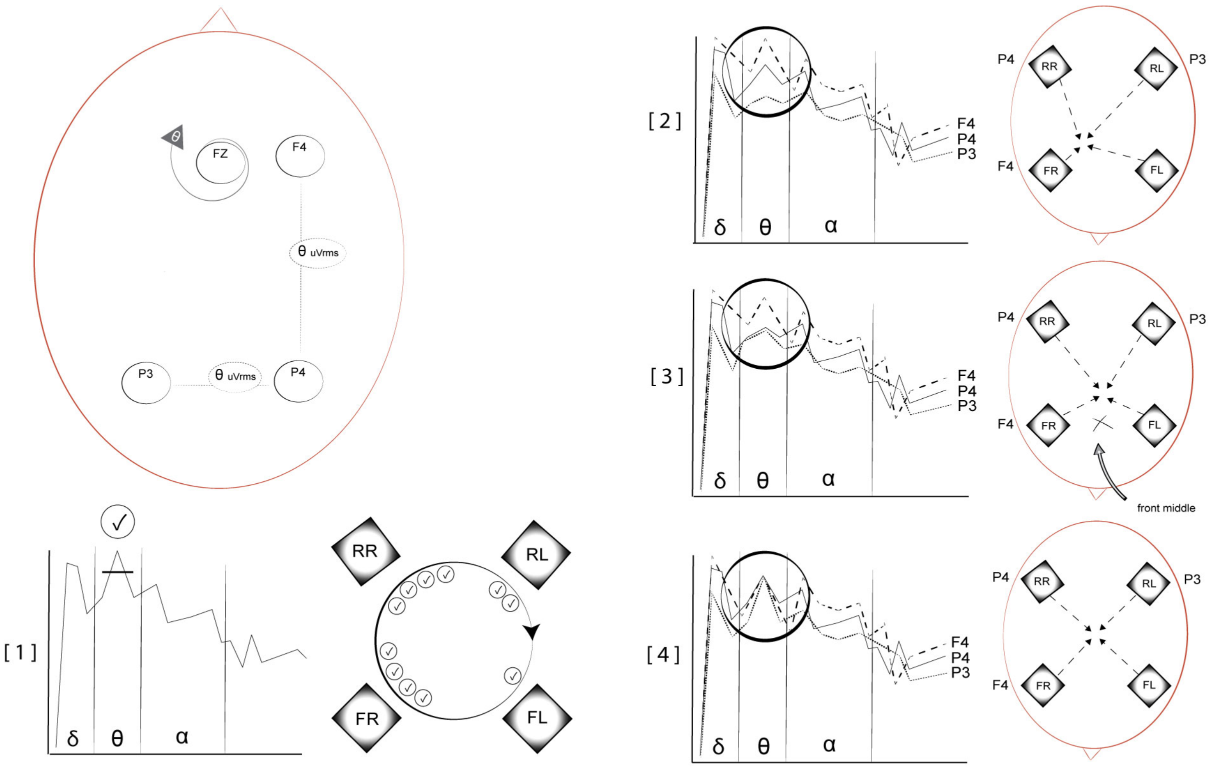

Figure 5.24: EEG cap labelled with the four brain areas (top left) where I measured signals for the neurofeedback protocol (Fz) and the coherence sonification (F4, P3 and P4). Four groups of FFT plots (bottom left and right) with relevant sound spatialisation. Group [1] illustrates how BCMI-2 spatialised the shaker sounds in a circular motion around the audience when theta was above the neurofeedback threshold. The other three groups (right) illustrate how the system mapped intra- and cross-hemispheric theta amplitude coherence to the spatialisation of the electro-acoustic drum effects. In Group [2], sounds are loudest close to the front right (FR) due to theta being strongest in F4 and stronger in P4 than in P3. In Group [3], sounds are loudest in the front-middle due to theta being strongest in F4 but comparable in P4 to the strength of theta in P3. In Group [4], sounds are centred in the middle of the room, as all three theta signals have similar amplitudes.

The transformation and spatialisation in the electro-acoustic drum effects track continued my attempt to interpret brain activity in a way that could help induce the desired altered state. First, the granular synthesis and delay effects added to the live drumming aimed to help listeners connect the ordinary (dry/acoustic) to the non-ordinary (wet/transformed) world. Second, in addition to the transformed sounds' continuous motion sonifying theta amplitude coherences, these movements also symbolised how visual imagery of seemingly autonomous 'beings' often move in my shamanic journeys — providing I manage to produce a breakthrough. To clarify, I do not consider this coherence to spatialisation mapping to be part of the neurofeedback protocol as it was not set up for operant conditioning. Instead, it was an abstract artistic interpretation aiming to support the immersion into the SSC.

The counter track is more straightforward. In it, inspired by the voice of Robert Monroe in the *Gateway Experience* (Monroe Institute, 1962b), I announced each level with my voice counting backwards from Level 16 to Level 0. I added this track to help recall where in the soundscape my meditation feels becoming deeper.

5.5.3.2 Ndefs

This enhanced soundscape required some careful considerations regarding several technical and aesthetic aspects, such as the transformation of live acoustic sounds and their surround sound spatialisation. To better understand how this part of the system would function in a live setting, I first tested it in a collaborative performance with live audio from singers, speakers and instrumentalists (Ryan, 2019). Within the Shamanic Soundscape Generator, sounds in all tracks use the `Ndef` object. This object provides simplicity when routing buses (audio and control signals) and allows for the use of the `NdefMixer` GUI to fine-tune the sound mix before the start of a performance (Fig. 5.25).

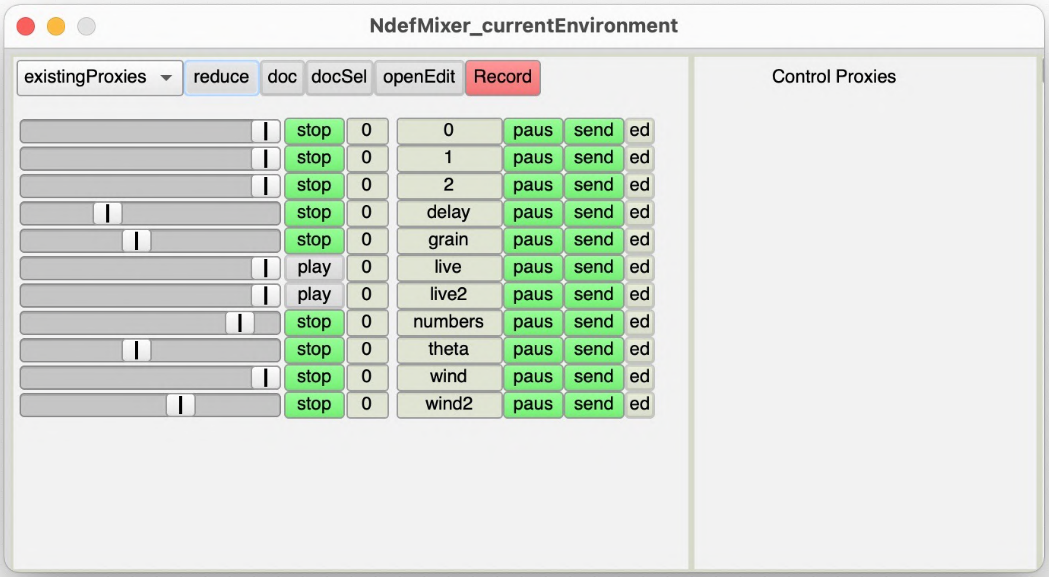

Figure 5.25: BCMI-2's NdefMixer GUI in the performance.

5.5.3.3 Shorter duration and no breakthrough

I set the length of the soundscape for the BCMI performance to 20 minutes, 10 minutes shorter than the soundscapes generated in the NFT setting. The main reason for this was to ensure that people in the audience who might lack interest or struggle with music-guided meditation would not become irritated by a too-lengthy, repetitive composition. As shamanic journeys in core shamanic practices often use 15- or 30-minute audio files (Harner, 1993), I could have gone below 20 minutes but decided against it for the following reason. As my brainwaves would be used in the performance, the duration had to be informed by the time I usually need for a mental shift, which on average is at least 15 minutes with BCMI-2 or when doing my own drumming without this system. In the end, while I managed to induce some internal visual imagery around Level 5, I did not have the breakthrough I was hoping for.

5.5.4 Deployment

I recorded the following digital files during the performance:

1. a screencast of the computer screen, including SuperCollider's editor, the FFT plot, etc.
2. four high-resolution mono audio files archiving SuperCollider's output channels
3. a high-resolution audio file archiving my acoustic drumming with a dynamic Zoom H1 microphone
4. a wide camera shot capturing the audience and the performance from a distance
5. a close-up camera shot capturing my drumming
6. a BCMI data file containing raw and classified EEG signals as well as soundscape-related values

In addition to these items, I asked audience members who experienced visions during the performance to interpret them via drawings, for which I provided note clipboards, paper and coloured pencils.

I used Files 1-5 to archive the presentation and the performance in audio-video formats, the audio files (2 and 3) and the drawings to create an audio release in stereo and surround formats and the BCMI data file (6) for an off-line data analysis in SuperCollider.

5.5.4.1 Audience feedback

While I did not have a breakthrough, the system was stable throughout the performance, and the overall feedback from the audience was positive. In addition, some participants managed to induce visual imagery while meditating with me, which they interpreted in drawings after the performance (Fig. 5.26).

In addition to drawing, some audience members shared their visions in writing as well:

> I was climbing a very big mountain for a long time, then many other people joined to climb the mountain; after a long time, we arrived on a plateau where there were already a lot of animals and other people. We sat together around a fire, then listened [to] the drums and danced for a while. We sat once again around the fire and then it was like a union of all our consciousness, a dissolution of our bodies to become just one consciousness. For all the final part it was only clear consciousness without new visualisation.

In general, the audience's feedback in the Q&A and later via email was that they felt relaxed and present (mindful) during the performance. However, one comment was different:

> I have listened to the performance music and I am a bit concern about it. Maybe other people present at the performance have experienced dark visions [as well], but they were shy and they didn't say.

As this comment concerned me, I met with this person to explain the methods used in the performance and discuss his vision. As I was in no position to provide any psychological analysis or support regarding his experience, I planned to suggest that he look for relevant help, perhaps through the NHS. However, our discussion highlighted that he had been investigating spiritual practices, and he assured me that he could deal with the situation on his own. Since then, we have been communicating regularly regarding drumming workshops we could organise together, and I have no further concern for his well-being.

Figure 5.26: Drawings by the audience after the performance.

Figure 5.27: Digipack release of *Shamanic Soundscape* - *Level Two* (2019).

5.5.4.2 Audio-video archives

Another creative output of this project is the audio release titled *Shamanic Soundscape - Level Two* (Hofstädter, 2019e), containing three mixed and mastered soundscapes. BCMI-2 generated the first soundscape (*Playing*) in the rehearsal and the second (*Jester*) during the performance. I produced the third soundscape (*Jester - Binaural Beats Version*) a few months later for a listening study investigating how binaural beats could improve ARE.[13] The release on the online audio distribution platform Bandcamp provides stereo files of all three soundscapes for streaming and downloading and additional surround files of the first two soundscapes for downloading. The stereo files are also available on a physical CD in a Digipak case (Fig. 5.27). The surround version of *Jester* is available for online streaming on the online platform Surround Music One (Hofstädter, 2019c). The release's cover art features one of my paintings (Hofstädter, 2005) with alterations inspired by the cover art of the SHAMAN journal by ISARS (1993) seen in Fig. 5.28. The eight-page booklet in the Digipak's inner sleeve contains the audience's drawings.

Figure 5.28: Cover art for SHAMAN journal. Image courtesy of ISARS.

Other creative outputs include two videos produced using the files archived at the performance, primarily to generate interest for forthcoming research projects. I first made a video collage featuring computer code to make an impression on technically minded people. Later, I made an alternative, more minimal version of this video with annotations clarifying the neurofeedback protocol used, and I added additional binaural beats to the audio (Fig. 5.29).

5.5.4.3 Offline data analysis

I plotted the performance's BCMI data with a customised version of the `nf-plotter-example.scd` file outlined in Section 5.2. As mentioned earlier, my meditation did not produce a breakthrough during

[13] This study is not yet completed but is briefly introduced in the following Section 5.6.

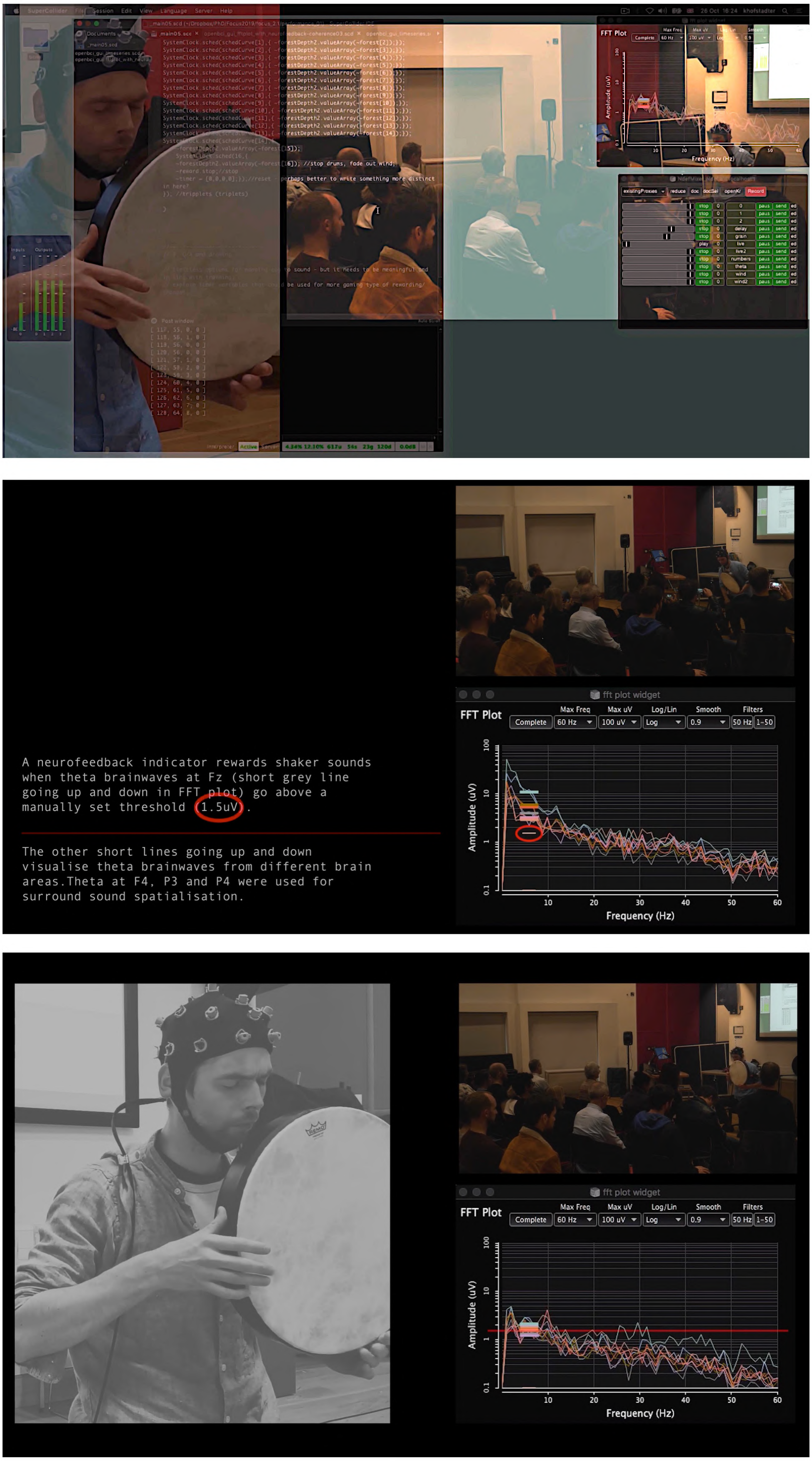

Figure 5.29: Snapshot (top) from the first performance video collage (Hofstädter, 2019d). Snapshots from the second video, in which, between 0:51 and 2:10, a clear FFT plot and annotations clarify how the neurofeedback protocol uses theta at Fz to trigger shaker sounds (middle). Last, a more minimal arrangement of video elements that were used to document the event (bottom). (Hofstädter, 2022b)

this performance, which I believe was primarily due to my inability to stop thinking about the technical complexities around me. In the top two parts of Fig. 5.30, we can see that my neurofeedback success rate was around 50% throughout the performance, indicating no increase in my theta at Fz.

5.5.5 Conclusion

Research and project objectives

The project addressed RO3 — it demonstrated BCMI-2's suitability to support meditation practices in an artistic performance setting. The project addressed all its objectives. The system was stable throughout the performance, and its use provided insights on how it can be further improved and used for live performance and off-line compositional work (e.g. digital audio releases). The project also encouraged people to participate in the subsequent listening studies and prompted researchers to start discussions with me regarding future collaborations.

New objectives

The project highlighted some weak points of BCMI-2. Apart from the speakers, their stands and XLR cables for sound, the projector for visuals and the two tripods used (one for the OpenBCI board and the other for a DSLR camera), all other equipment for the performance is small and light enough to be carried by one person and includes the following:

- laptop
- soundcard
- SM57 (soundcard input) and Zoom H1 mic (additional recording)
- EEG cap and OpenBCI board
- frame drum
- mobile phone connected to the laptop
- gooseneck mobile phone holder for providing adjustable camera angles
- external DSLR video camera

Although this mobility allows me to perform with BCMI-2 at distant locations (even if I have to travel on public transport), an extra pair of ears is still needed when calibrating the nuances of the surround sound mix. Fortunately, at the above-described performance, I had an extra day to set up and ask for help with mixing; however, a few days later, at a different location, I had only half an hour to set up and no support for the sound mix. My discomfort with the sound throughout this (fortunately more informal) performance highlighted how crucial it is for this project that I have adequate time to set up and the assistance of another person for a soundcheck.

Another future objective relates to obtaining feedback from the audience. Although I allocated around 15 minutes at the end of the event for Q&A and drawing, I did not ask for any written feedback that I could quantify later. That it would have been useful to have a short survey at the end of the event was only

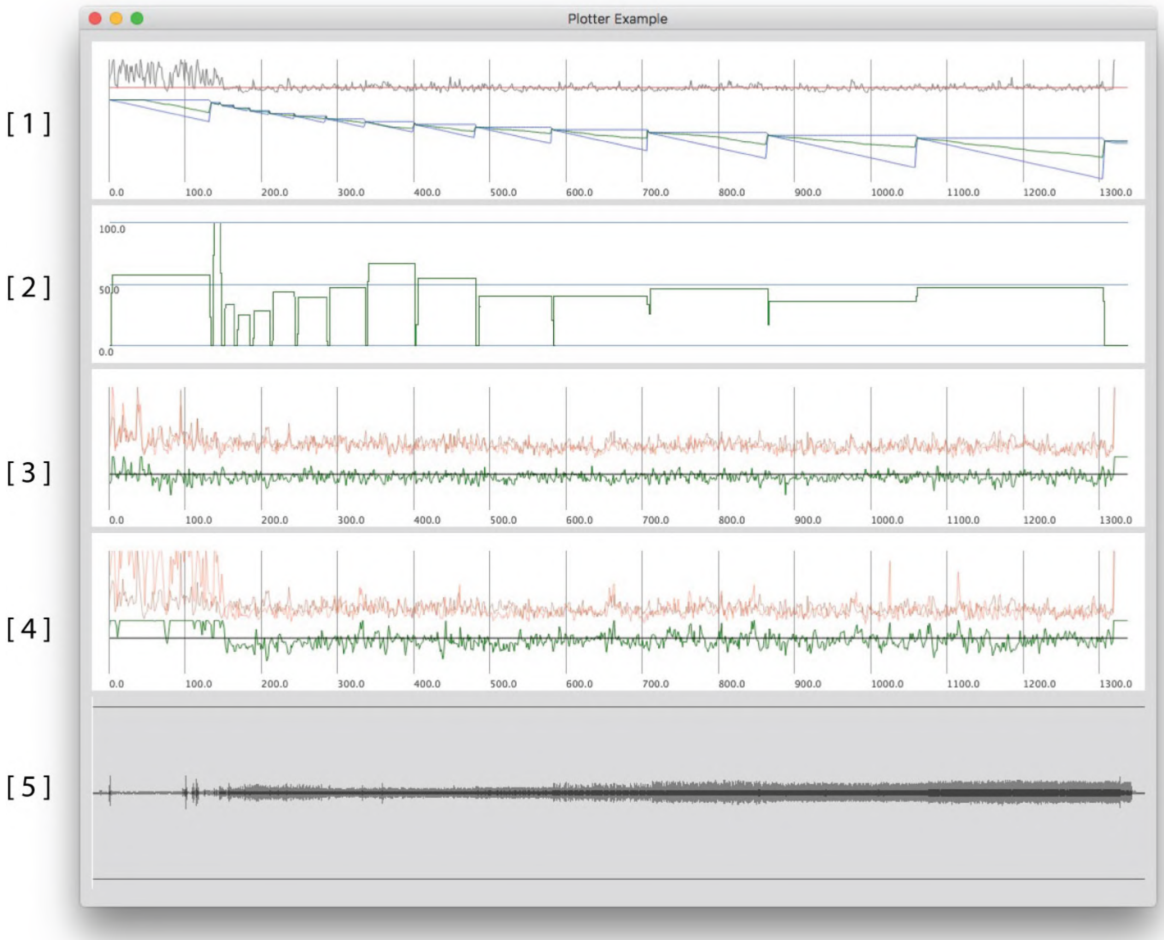

Figure 5.30: BCMI data plot of the performance. Part [1] shows theta median at Fz (wiggly grey line); neurofeedback threshold (horizontal red line); soundscape level durations (blue triangles), and (4) averaged neurofeedback success rates for each level (green lines in the blue triangles). The closer the green line gets to the bottom right corner of the blue triangle, the higher the neurofeedback success rate at that level. Part [2] shows the success rates again, with higher green steps indicating higher success rates. Part [3] visualises amplitude coherence between two theta energies recorded at F4 (wiggly red line) and P3 (wiggly grey line). The wiggly green line shows these two signals' amplitude coherence. The value of the amplitude coherence is between -1.0 and 1.0. The black horizontal line indicates 0. The higher the value, the higher the coherence between the two theta signals (1.0 is high coherence, and -1.0 is no coherence). Part [4] visualises amplitude coherence (again), but here between P3 and P4. Part [5] visualises the recorded audio file and allows playback.

realised when I received comments from only 5% of people in the audience through the festival organiser's online system a few weeks later. The issues with gathering data through the event organiser's system are that the questions are not linked to my work and that I do not have control over when my audience receives these forms. Therefore, in the future, I will consider gathering feedback before the audience leaves the event.

The dark vision experienced by one person in the audience highlighted that altering the state of mind can induce both pleasant and unpleasant experiences. While I warned audiences about the possibility of a 'bad trip' and was prepared to debrief and direct people to mental health lines, I will also become trauma-informed by completing the Mental Health First Aider (MHFA) training.[14] Another comment received after the event also highlights the importance of this objective:

> As one of the participants of Kris Hofstädter's presentation on drumming and meditation at ARU I thought Kris was competent at presenting and introducing the meditation. As a therapist it did occur to me, that people who are unfamiliar with meditation, might well have strange or even shocking impressions or visions that appear to them, stimulated by the drumming and silence. In these circumstances, deeply rooted images can surface into consciousness. Of course, if a participant is later assisted to process these impressions or visions, it is very positive. ~ Rhea Quien (Art Educator in Creative Expression Art, Therapist in Educational Kinesiology, Cambridge)

Next, Section 5.6 outlines how I used a shamanic soundscape without BCMI-2 to strengthen my understanding of ARE's potential.

5.6 Listening Study Testing ARE

5.6.1 Project overview

This project surveyed 84 participants in a listening study to strengthen my understanding of using ARE with decreasing tempo and rhythmic complexity for shamanic journeying. Based on the outcomes of the NFT sessions (Section 5.4), I set up a questionnaire with *Jester* (the soundscape recorded at the performance outlined in Section 5.5), gathered data using SurveyMonkey and analysed the data with OpenOffice and RAWGraphs (DensityDesign and Inmagik, 2013). To clarify, this survey did not use the BCMI-2 system with neurofeedback protocols or other real-time EEG sonification techniques. The rendered file of the soundscape was played with a Web audio tool embedded in the questionnaire. The main outcome of the survey was that most participants experienced an increase in focus (67%) and recalled being most focused towards the end of the soundscape. While this outcome enhanced my confidence in using ARE with gradually decreasing tempo and rhythmic complexity to support shamanic journeying, it does not yet contribute to scientific knowledge, as it is still necessary to test ARE (e.g. with increasing and unchanging parameters). The project also refined my goals and methods for upcoming studies (e.g. regarding calls for participation, questionnaires, data collection points, and creative data analysis).

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[14] I booked this training with MHFA England for Fall 2022.

Furthermore, it generated a mailing list of potential participants for upcoming studies. After this first study, I conducted a second listening study (n=23), testing how adding binaural beats to ARE affects participants' shamanic journeys. In this second study, participants were randomly chosen to listen to *Jester* or *Jester (Binaural Beats Version)* with closed eyes. This section only discusses the first survey. I will use the insights gained in the two studies to design a third study and new NFT sessions that employ scientific rigour. I also plan to write up these insights as a chapter for a handbook on the cross-cultural assessment of how we could use the ancient techniques of shamanic traditions for contemporary healing practices. While the completion of this project is still underway, preliminary results seemed interesting enough to report here, if for no other purpose than to inspire others.

Project time span: September 2019—August 2020

Supporting material:

- *Shamanic Soundscape - Level Two* | The digital audio release featuring *Jester*, the soundscape used in this study.

5.6.2 Goals

After demonstrating BCMI-2's suitability to support meditation practices in NFT and artistic performance settings to address RO3 (Sections 5.4 and 5.5), I sought to strengthen my research through a better understanding of ARE and relevant methodologies for questionnaires, data representation and the dissemination of creative research outputs. My objectives in this project were to

- design an internet survey based on the outcomes of the NFT sessions (Section 5.4)
- discuss drafts of this survey with shamanic practitioners and implement feedback
- disseminated the call for participation on relevant channels
- conduct the survey and provide support where needed
- investigate methods for data analysis providing aesthetic visualisation
- analyse the gathered data
- draw conclusions that can help design future projects
- increase others' interest in my work

These objectives were informed by the outcomes of previous projects; the literature review regarding meditation; my experiences of shamanic journeying; technical aspects of survey design, dissemination and analysis and discussions with relevant researchers and shamanic practitioners.

5.6.3 Design and development

I started my study with one SurveyMonkey questionnaire in English, but due to the interest of Hungarian people who do not understand English, I extended it with a questionnaire in Hungarian. Before I sent out the call for participation via social media and emails, the questionnaire was reviewed by The

Foundation for Shamanic Studies, an organisation for practising core shamanism established by Harner (1979) and by senior admins of two shamanic Facebook groups practising traditional shamanism (Facebook, 2007; 2019). While these reviewers appreciated my interest in shamanic journeying and helped shape the questionnaire, they also shared concerns about what they believe are essential differences between shamanic journeying and other forms of meditation with visualisation. More specifically, they were concerned that my participants were not required to have previous training in shamanic traditions and, therefore, would be uncertain about who or what was answering their questions and thus be confused by the spirit world. Following their suggestions, I continued relating the study to shamanic journeying in the introduction of the questionnaire but also implied that it is not the same:

> This survey attempts to collect the effects of a soundscape for meditation purposes supported by sonic driving. The sonic driving derives from the shamanic journey tradition but is not specifically a shamanic journey. The estimated completion time is 30 minutes, including a 20-minute meditation.
>
> **What is shamanic journeying?** Shamanic journeying aims to take participants on a trip to a non-ordinary reality, traditionally through drumming. Participants are encouraged to ask for clarity on a specific question throughout the journey.
>
> **How is this soundscape different from the traditional form?** You will hear an audio of drumming largely based on the traditional form, but with additional sound textures and more diverse rhythms.

The questionnaire asked participants to commit to two conditions. First, I asked them to carry out the study in an undisturbed environment to make sure they could relax with their eyes closed while listening to the soundscape. Second, I asked them not to eat for at least two hours before the study to ensure their bodies could better focus on the meditation experience instead on digestion.

Similar to the questionnaire used in my previous NFT sessions, the questionnaire in this project also had three parts, with additional and improved questions. The first part (Before Listening) gathered demographic data and data on how participants felt about their focus and emotional states before listening to the soundscape. In the second part (Listening), participants listened to the soundscape with closed eyes. The information in the questionnaire encouraged them to focus on the repetitive aspects of the drumming while also thinking about a question about which they would like to seek clarity. The third part (After Listening) gathered data on participants' focal and emotional states and how they thought the tempo and rhythmic changes supported their focus. Finally, at the end of the survey, I encouraged them to write and interpret their visual imagery – if they experienced any – in drawings.

I tested the technical aspects of the questionnaire on several computing devices, operating systems and browsers. Although I collected the responses anonymously, participants were asked to provide nicknames they could refer to in an email if needed.[15]

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[15] For more detail (e.g. the PDF version of the survey and the list of collection points), please see Appendix 4.

Figure 5.31: Poster advertising the first listening study using a well-known photograph of a Mongolian shaman by Sakair Pälsi taken in 1909. Image courtesy by Finnish Heritage Agency. The poster also received a custom domain (https://shamanicmeditation.info) to help people easily remember the URL. (The custom domain expired in November 2020.)

5.6.4 Testing

I disseminated the call for study participants through several channels, including social media groups related to methods proposing to help induce and maintain ASCs (e.g. Facebook groups and online forums related to shamanism, BCI, NFT, drumming and psychedelic music). I also advertised the study on my Twitter, YouTube and SoundCloud profiles and through personalised private messages on Facebook Messenger and email. For each target group, I used customised information and trackable URL links to help compare the effectiveness of these channels in later analysis. The poster I designed to advertise at suitable venues (e.g. meditation centres and music departments) can be seen in Fig. 5.31.

Initially, I intended the study to last for a month; however, many people requested an extension, so it went on for four months, from the end of November 2019 to the end of February 2020. Due to two people experiencing technical issues, one on an Android mobile device and the other due to a slow internet connection, I exported the survey to a rich text format and sent it to them via email with additional instructions. I then added their answers to the database manually.

5.6.4.1 Analysis tools

As I could not merge the data from the two questionnaires (English and Hungarian) within the SurveyMonkey platform, I could not use this platform's online analysis tools either. Therefore, data from both surveys were exported in .csv format and merged into one spreadsheet using OpenOffice software. In OpenOffice, the data was pre-processed and analysed using simple mathematics (e.g. `COUNTIF` and `SUM` functions). In order to recognise correlations and represent them artistically, I calculated values in OpenOffice and generated visually engaging graphs using RAWGraphs that were then adjusted in Adobe Illustrator. The outcome of the combination of these analysis methods can be seen in the tables and figures below.

5.6.4.2 Analysis

Most participants were between 25 and 45 years of age, and the group consisted of slightly more males than females (Tables 5.2, 5.3). Age and sex were not found to be correlated with other variables in the study.

Table 5.2: Number of participants in each age group.

Age Group	Number of Participants	%
Under 18	0	0.00%
18-24	9	10.71%
25-34	22	26.19%
35-44	28	33.33%
45-54	14	16.67%

Age Group	Number of Participants	%
55-64	6	7.14%
65+	5	5.95%

Table 5.3: Number of participants by sex.

Sex	Number of Participants	%
Female	36	42.86%
Male	48	57.14%

About half of the participants had no previous experience with shamanic journeying, while most considered their meditation practices as frequent ('often') (Tables 5.4, 5.5).

Table 5.4: Number of previous shamanic journeys experienced by participants.

Number of Previous Shamanic Journeys	Number of Participants	%
0	45	53.57%
1	7	8.33%
2-10	18	21.43%
10-25	1	1.19%
25+	13	15.48%

Table 5.5: Regularity of participants' meditation experiences.

The Regularity of Meditation	Number of Participants	%
Never	15	17.86%
Rarely	16	19.05%
Sometimes	16	19.05%
Often	37	44.05%

An expected correlation was found between participants' beliefs and experiences with shamanic journeying; people who labelled their beliefs as 'Shamanism' or 'Spiritualism' indicated a greater number of experiences with shamanic journeying. In contrast, people who did not associate themselves with any belief system ('None') and people with more traditional beliefs (e.g. 'Christianity', 'Buddhism' and 'Islam') indicated no experience with shamanic journeying (Fig. 5.32).

Most participants did not use any mood-altering substances before the study (Table 5.6).

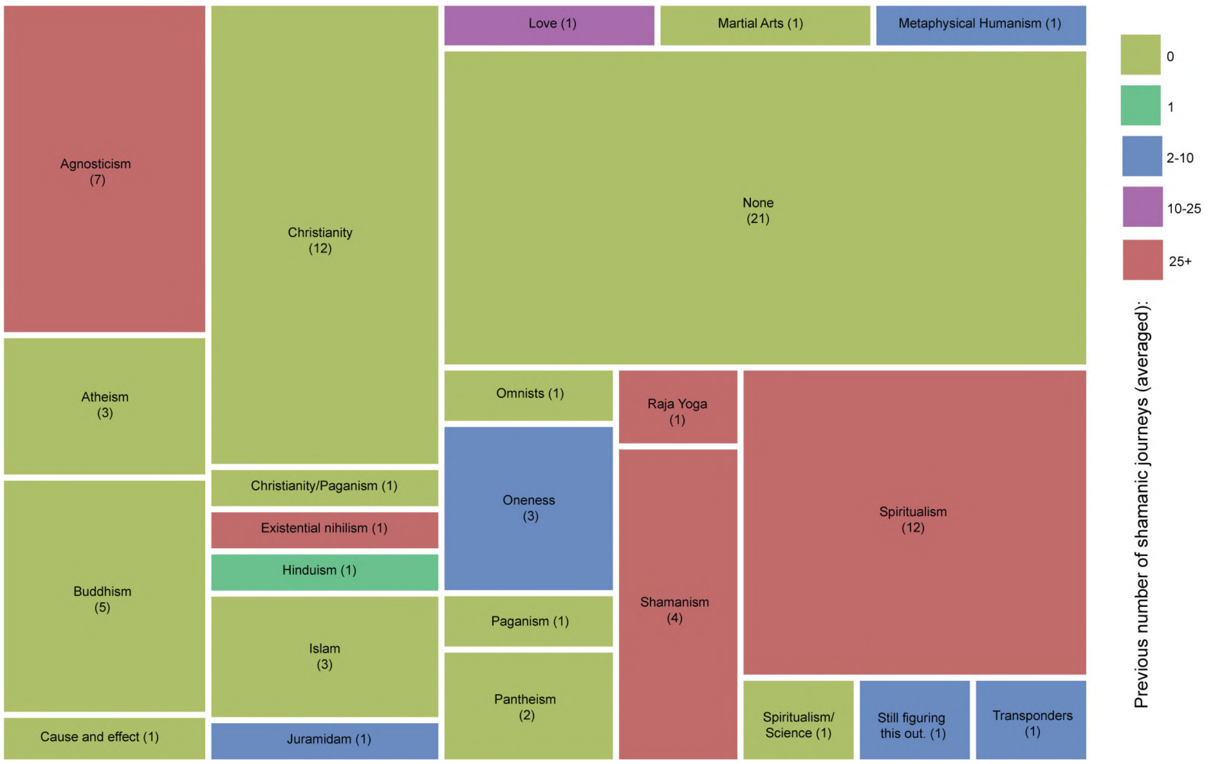

Figure 5.32: Correlation between belief groups and experience with shamanic journeying. The size of each belief group is indicated by the sizes of the rectangles and the values presented. Experience with shamanic journeying is indicated with colour.

Table 5.6: Reported substance use of participants.

Substance Used	Number of Participants	%
No	59	70.24%
Yes	25	29.76%

Out of the 25 participants who used mood-altering substances, 22 used caffeine, one used cannabis and two used both caffeine and cannabis. Substance use was not correlated with any other variables in the study.

Slightly less than half (46%) of the participants experienced internal visual imagery, which correlates with the number of participants who received clarification regarding a question they asked during their shamanic journey (49%) (Tables 5.7, 5.8).

Table 5.7: Participants reporting visual imagery.

Visual Imagery	Number of Participants	%
No	45	53.57%
Yes	39	46.43%

Table 5.8: Participants reporting clarification.

Clarification Received	Number of Participants	%
No	43	51.19%
Yes	41	48.81%

However, the more detailed graphical interpretation in Fig. 5.33 suggests that visual imagery was not required for clarifications: one-third of the participants with no visual imagery received clarification, while one-third of the participants with visual imagery did not. In addition to linking visual imagery with clarification, this figure also relates clarification to pre-listening levels of focus and shows how this focus changed during listening. As seen, there does not seem to be any correlation between these four variables. While Table 5.9 shows that most participants experienced an increase in focus (67%), there is no observable correlation in Fig. 5.34 between this increase and whether participants found it easy or difficult to focus on the drumming, nor is there a relationship between visual imagery and a change in focus.

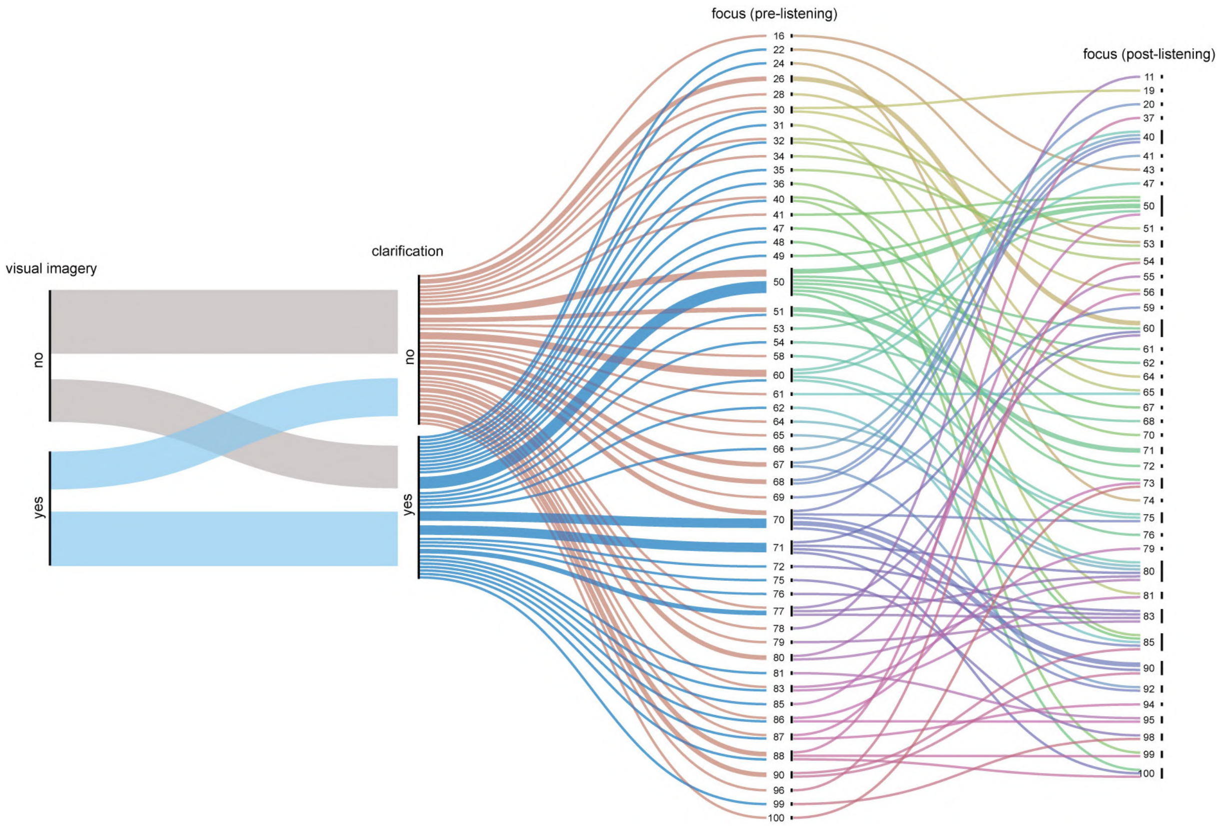

Figure 5.33: Correlation between visual imagery (experienced or not), clarification (received or not) and focus change (increase or decrease when comparing pre- and post-listening).

Table 5.9: Participants' focus increase/decrease after listening to the soundscape.

Focus After Listening	Number of Participants	%
Decreased	28	33.33%
Increased	56	66.67%

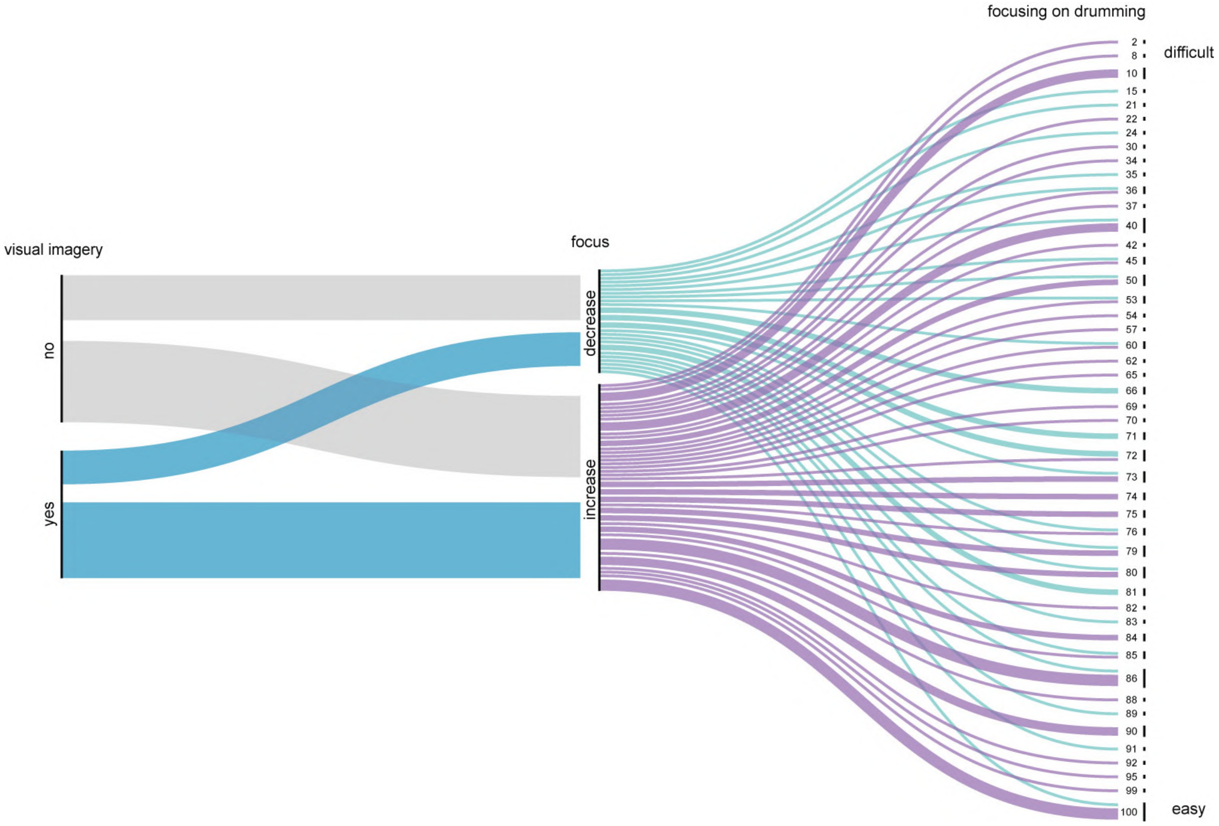

Figure 5.34: Correlation between (1) visual imagery (experienced or not), (2) focus change (decrease or increase) and (3) participants' perception of how easy or difficult it was to focus on the rhythms in the music.

However, as seen in Table 5.10, most participants recalled being most focused towards the end of the soundscape (Level 6—Level 3), which besides most participants experiencing an increase in focus during the soundscape, was another outcome I had hoped to observe in this study.

Table 5.10: Levels where participants reported the highest level of focus.

Most Focused (levels)	Number of Participants	%
Level 16 (first outer layer)	5	5.95%
Level 15	1	1.19%
Level 14	2	2.38%
Level 13	3	3.57%
Level 12	5	5.95%

Most Focused (levels)	Number of Participants	%
Level 11	4	4.76%
Level 10	4	4.76%
Level 9	1	1.19%
Level 8	9	10.71%
Level 7	3	3.57%
Level 6	**8**	**9.52%**
Level 5	**12**	**14.29%**
Level 4	**8**	**9.52%**
Level 3	**11**	**13.10%**
Level 2	4	4.76%
Level 1 (most inner layer)	3	3.57%
Level 0 (outside of forest)	1	1.19%

This grouping can also be seen in Fig. 5.35, which depicts the relationships between other variables. The figure shows that, for this study, most people who were highly experienced in shamanic journeying (JS:25+; n=13) not only meditated often but also experienced visual imagery, received clarification, had an increase in focus and found focusing on the rhythmic changes to be easy or slightly easy. Data from participants with no experience in shamanic journeying (JS:0; n=45) is more varied. For example, only 33% of these participants (n=15) experienced visual imagery, but this experience was not correlated with any of their other data (change in focus, clarification, frequency of meditation or the ability to focus on the rhythmic changes). Also, while the majority of participants in this group (76%) recalled being most focused towards the end of the soundscape (Level 9—Level 1) – similar to people highly experienced in shamanic journeying – many (24%) recalled being most focused in earlier levels (Level 16—Level 11). Contrasting the data of these two groups (JS:0 with JS:25+) shows that the participants who were highly experienced in shamanic journeying (with one exception) had similar experiences in this study, while participants with no experience with this meditation technique had more dissimilar experiences.

As seen in Fig. 5.36, the most successful collection point (one of the trackable URL links created in SurveyMonkey) was the one used on my personal Facebook wall and in four shamanic Facebook groups. [16] The most amalgamated responses were linked to the collection point used under my YouTube video archiving the performance. It is my belief that, Jeff Strong (the creator of REI outlined in Section 3.4) shared this URL with his drumming classes at the beginning of February 2019, and therefore, these responses are likely linked to him, his students and associates.

[16] Unfortunately, I did not set up separate collection points for these channels at the very beginning of the study. I soon understood this was a mistake, but I felt that editing the calls in my Facebook group posts would confuse admins (as they need to authorise changes) and therefore did not amend my posts.

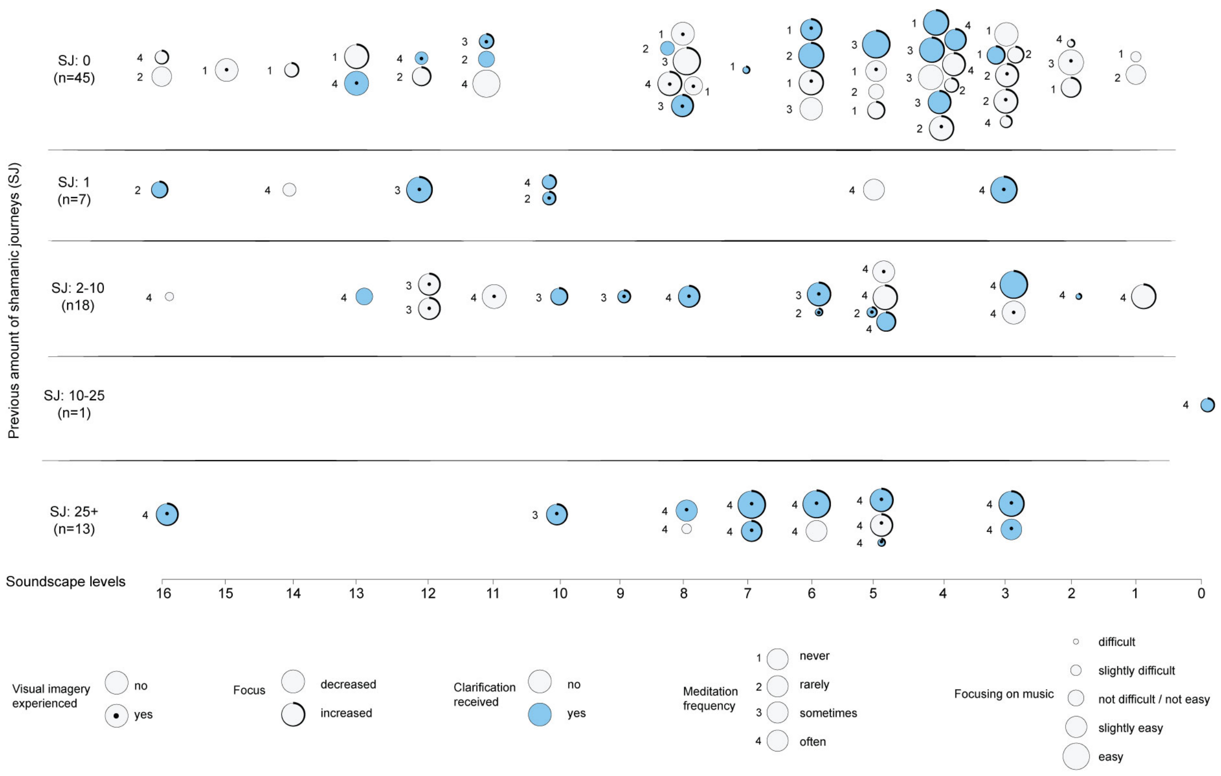

Figure 5.35: Correlation between (1) presence of visual imagery (experienced or not), (2) focus change, (3) clarification (received or not), (4) frequency of meditation and (5) participants' perception of how easy or difficult it was to focus on the rhythms in the music.

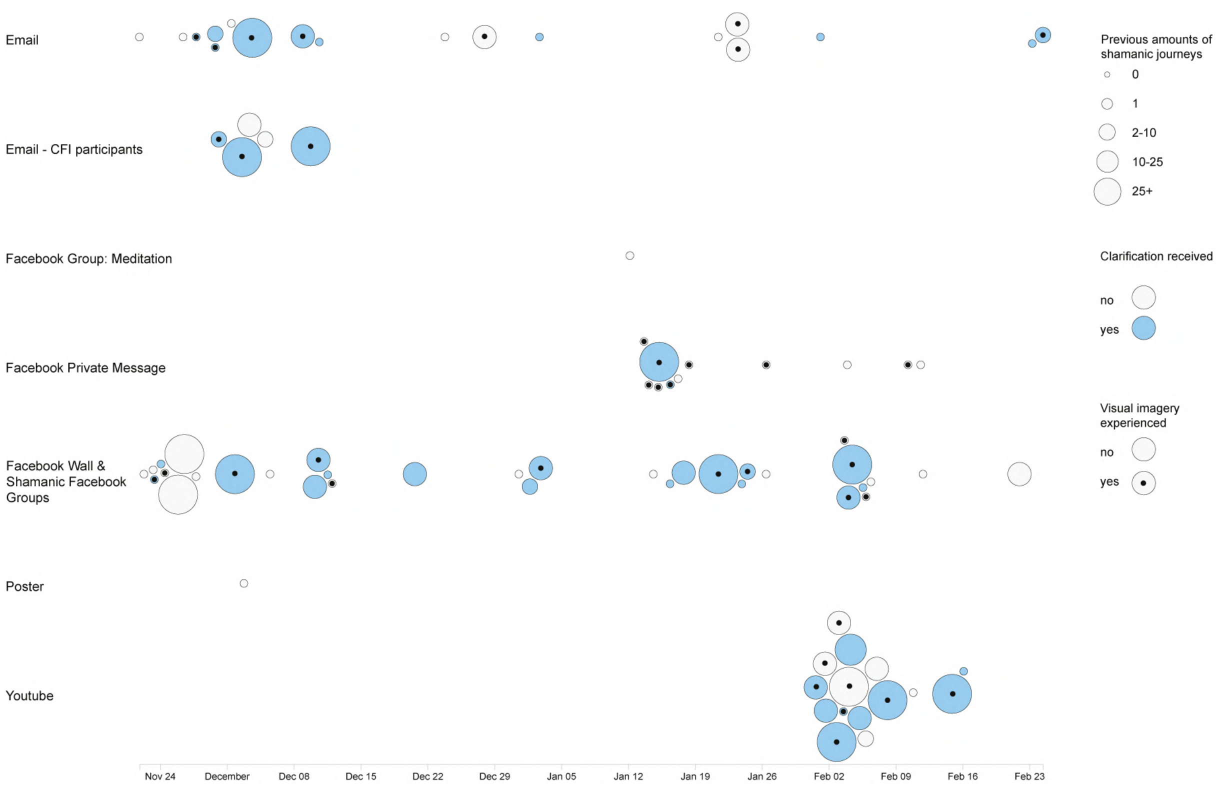

Figure 5.36: Correlation between (1) collection points, (2) date, (3) the number of previous shamanic journeying experiences, (4) clarification (received or not) and (5) visual imagery (experienced or not).

My two main observations from the above analysis are as follows. First, most participants experienced an increase in focus (67%) and recalled being most focused towards the end of the soundscape. While both of these outcomes are desired for deepening a shamanic journey, it is not possible to directly link these changes specifically to ARE with gradually decreasing tempo and rhythmic complexity, as the study did not test other ARE parameters (e.g. an increasing or unchanging tempo and rhythmic complexity). I plan to address this through forthcoming projects. Second, of the 45 participants with no experience in shamanic journeying (JS:0), only 8 (18%) meditated often, while of the 13 participants who were highly experienced in shamanic journeying (JS:25+), 12 (92%) meditated often. When comparing the data of these 8 with these 12 participants regarding their visualisation experience, we can see that a high level of experience in shamanic journeying helped induce visual imagery (Table 5.11). This difference might be related to the fact that practitioners of other types of meditation may not exercise visualisation when they meditate with their eyes closed.

Table 5.11: Correlation between the number of previous shamanic journeying experiences and whether or not visual imagery were experienced. Of participants with no experience in shamanic journeying, 38% had visuals, while 83% of participants with a high level of experience had visuals.

Number of previous shamanic journeying experiences	0	25+
visualisation experienced	38%	83%

5.6.5 Conclusion

Research and project objectives

This listening study achieved all its objectives and has strengthened my understanding of ARE and survey methodologies, including creative representation of data — all of which I will implement in designing new research with and without BCMI-2.

New objectives

Due to some disadvantages of SurveyMonkey (e.g. limitations of certain survey-building elements and the high monthly cost for custom options such as multi-lingual surveys and surveys with over 10 questions), I plan to explore other online tools (e.g. Qualtrics) or build one myself with HTML programming for my future studies. Also, in order to compare my data with other researchers' data in similar listening studies, I will explore these researchers' methods and, if possible, adjust my methods to align with theirs. I will also improve my new survey by asking more specific questions (for instance, about the regularity of participants' meditation practices). Furthermore, I will add more questions (for instance, to find out whether participants' meditation sessions were distracted by anything in the study environment or not). While the combination of OpenOffice, RAWGraphs and Adobe Illustrator proved suitable for analysis and aesthetically visualising data, I started exploring other statistical tools (e.g. R and SPSS) for statistical computing and graphics to develop my analytical skills further. As mentioned, this commentary only discusses the first survey. I will analyse the second survey after the completion of this doctoral research. Then, I will use the insights gained in these surveys to design new NFT settings for BCMI-2 that employ scientific rigour.

5.7 Personal Journeys and Engagement with People

An additional aspect that might also help the desired mental shift is related to the soundscapes' 'liveliness'. BCMI-2 creates this liveliness by using ever-changing brainwaves, randomised audio selections and other processes that we can set to be unpredictable, e.g. to random level lengths. In essence, every soundscape generated is slightly different. While meditating, we can use this liveliness as the subject of our focus, similar to how we use open, non-reactive curiosity when observing our inner or outer environments with receptive meditation techniques. This in-determined nature of the soundscapes, I believe, can help increase immersion in a Cagian sense:

> Then the answers, instead of coming from my likes and dislikes, come from chance operations, and that has the effect of opening me to possibilities that I hadn't considered. Chance-determined answers will open my mind to the world around. (Montague, 1985)

For me, the most effective way to meditate with the shamanic soundscapes (whether generated in real time with the BCMI-2 system or played back from a recording) is to gradually shift from a more narrowly focused to a more receptively concentrated state of mind. To achieve the more narrowly focused state, I first 'zoom in' and try to focus strictly on a specific aspect of the soundscape. For instance, this aspect can be the gradually changing rhythmic patterns or – when trying to go even further – the micro-sounds that emerge in these patterns. This first step, I believe, is similar to how practitioners of Transcendental Meditation focus on a mantra:

> The mantra, then, is not an object of concentration-absorption, but rather an anchor to keep attention from being captured by the objects that pass through the mind. (Washburn, 1978)

Once whatever I have been focusing on has provided a stable anchor for my awareness to latch on to, I gradually allow parts of this focused awareness to become more receptive. One by one, I use these freed-up parts to start paying open, gentle and non-reactive attention to other aspects of the meditation experience. For instance, these aspects can be the continuous noise in the soundscape, my heartbeat and breathing or — if not using headphones — the noise of radiators, the traffic, and my neighbour building something in his garden. Once my awareness is both stabilised and wide open to absorb information without actively analysing it, the flashes of abstract visual imagery entering my mind become gradually longer and longer until eventually, with a breakthrough, merged into a continuous SSC experience. Based on my experience and the outcomes of this project, I believe my shamanic soundscapes have — with and without the BCMI-2 system — strong potential to induce and maintain the SSC, especially if listeners have previous experience with meditation using visualisation techniques.

Engaging with people in this project was challenging in a variety of ways. Engaging with participants in the NFT sessions was relatively easy, as I had only one person to attend to and a technical setup that I had tested several times using my brainwaves in the same room. The sessions were pleasant experiences. I meditated beforehand and stayed as mindful as possible during the sessions, which helped me engage with the participants calmly and purposefully.

However, working in the performance setting was different. Despite rehearsing and meditating several times before the event, the highly technical setup and over 60 audience members destabilised my confidence in my abilities for a short time at the start. While I gradually regained most of my confidence during the first part of the event (the presentation), my stress completely disappeared within seconds when my eyes closed, my fingers touched the drum, and BCMI-2 began generating the soundscape. In retrospect, assuming that the people around me were meditating also helped — I felt supported.

Working with people in the listening study was challenging in both the design and the dissemination stages. The difficulty was caused by not truly understanding the nuances that separate traditional and core shamanism and, therefore, not understanding the occasional disagreement between these two groups. Not having a traditional shamanic lineage (I have not been initiated into any shamanic tradition) nor having taken part in core shamanic workshops often made me feel like an outsider when asking for guidance. I communicated with associates of these groups primarily through Facebook groups, personal texts and voice messages via Facebook Messenger and occasionally via emails. Although admins of these groups and heads of shamanic organisations were always respectful, helpful and supportive of my work, they were also critical of it. The main issue both sides had with the study was that participants who do not know the shamanic universes might enter an ASC while listening to the soundscape, and there, they would confuse helpful spirits with harmful ones. I still do not clearly understand the seemingly autonomous entities I have encountered in my shamanic journeys, so I appreciate and respect these concerns. These entities could be interpreted as agents independent of my psyche's core (the ego), as, for instance, explained by traditional and core shamanism (Harner, 2013), while from an analytical psychology-based perspective, I could explain them using Jungian archetypes or shadows (Jung, 1960). To understand what these entities are, I plan to study literature on the overlap between these two perspectives (Groesbeck, 1989; Noel, 1998; Charet, 1999) and design a method for meaning-making based on how (Boyle, 2007) used the works of transpersonal theorists Ken Wilbert and Stanislav Grof and psychologist Carl Jung. I will support the design of this method by investigating research by Rock and Krippner (2011) on the ontology, epistemology and necessary conditions of shamanic journeying and the issue of realism in these journeys.

Chapter 6

Conclusion

This chapter first clarifies how the research question and objectives (Section 1.4) were addressed. It then outlines my contribution to knowledge and proceeds to offer recommendations to developers of future BCMI systems. After that, I will finish by briefly introducing new research goals that go beyond the scope of this thesis.

6.1 Research Question and Objectives

To answer the research question, 'How can an affordable and open-source BCMI system be created to support meditation practices in NFT and artistic performance settings?', I addressed all of my ROs:

RO1: The literature review identified EEG correlates (neuromarkers) of meditative states and specific methods that can help induce and maintain these states (Sections 3.2, 3.3, 3.4 and 3.5).

RO2: The research developed the affordable and open-source BCMI-2 system based on the literature review findings (Sections 5.1 and 5.2).

RO3: The research tested BCMI-2's suitability to support meditation practices in NFT and artistic performance settings (Sections 5.3 and 5.4).

RO4: Based on the knowledge gained, I provide recommendations for researchers who are interested in using BCMI-2 or developing new BCMI systems to support meditation practices in NFT and artistic performance settings.

6.2 Contribution to Knowledge

By addressing these objectives, my research contributions are

- the creation of the BCMI-2 system and

- the recommendations based on the knowledge gained while developing and testing its suitability to support meditation practices in NFT and artistic performance settings.

6.2.1 BCMI-2 system

BCMI-2 is a stable system combining two entrainment methods in a novel way to support meditation practices: neurofeedback protocols and ARE. It embeds the neurofeedback reward sound as an integral element within the ARE, creating interactive and engaging soundscapes. BCMI-2 uses an affordable research-grade OpenBCI board to measure, digitalise and amplify multi-channel EEG, combined with the free audio programming environment SuperCollider for the remaining interfacing steps. BCMI-2 is fully open-source and, from the acquisition step onwards, customisable within one programming environment (SuperCollider). Clarity is provided by removing the need to run multiple software applications or IDEs simultaneously (e.g. one to process EEG and another to generate music). Finally, for those interested in developing new BCMI systems based on BCMI-2, SuperCollider offers high-quality audio and versatile composition tools and a vibrant research community available for help if needed.

As we can practise various meditative states with different musical methods, BCMI-2's customisable steps for electrode location, feature extraction, classification, mapping and sound control parameters could be valuable for:

- NFT practitioners who wish to design immersive soundscapes for neurofeedback protocols
- artists who wish to express themselves with physiological computing
- meditation practitioners who wish to understand meditation from a scientific perspective

Users with programming skills can customise BCMI-2's neurofeedback protocols and ARE parameters. We can select up to eight channels to record raw EEG signals and extract multiple frequency bands and phase coherence features from these signals. We can classify these features and then map them to sound control parameters for NFT or other, more artistic sonification purposes. Furthermore, we can adjust the tempo and rhythmic variability of the ARE generator and replace the default frame drum samples with different ones. Also, BCMI-2 can spatialise sound in stereo or 4.0 surround. Although this research only tested the system's ability to induce and maintain the SSC, by adjusting these parameters, we can entrain other meditative states (e.g. related to strong alpha brainwaves or hemispheric coherence).

We can use BCMI-2 in NFT and artistic performance settings

- with the same setup as documented in Sections 5.4 and 5.5 to induce and maintain the SSC [1] or
- by customising the system (e.g. the neurofeedback protocol and ARE parameters, the soundscape's sounds and length) to help induce and maintain other meditative states.

[1] Section 5.7 provides insights into how I meditate to induce and maintain the SSC while listening to the shamanic soundscapes generated by the system.

As both of these options require some programming skills, ultimately, BCMI-2 is still a prototype system for use by technically skilled people.[2]

In May 2021, I discussed this proof-of-concept system with NFT experts, whose positive feedback included the following:

Feedback regarding the high-quality audio and customisability of BCMI-2:

> It's exciting to see that Krisztian's research focuses on high-quality audio that's highly customized to create cutting-edge bio/neurofeedback experiences. I'm intrigued by the potential of a system that generates music in real-time intending to train and entrain certain mental states by harnessing individually generated music. We're delighted to support this scientific, beautiful, and artistic approach to edutainment, and its potential to enhance the human experience of millions. ~ Patrick Hilsbos, CEO @ Neuromore — neuromore.com

Feedback regarding the aesthetics of auditory NFT and the importance of aligning aspects of the feedback with aspects of the desired mental shift:

> I agree with your perspective that the quality and pleasantness of the sounds are crucial for meditation or induction of inwardly directed attention. After all, everything affects the brain, not just contingent neural feedback, but any kind of stimulus, so we want to make sure the stimuli we use are aligned with our purpose of inducing meditative mental states. Your research project sounds very interesting - I'm sure it would be beneficial to many! ~ Revital Yonah, EEG technician @ BetterFly — btr-fly.com

Feedback regarding the importance of researching the effective use of sound in NFT:

> From our conversation, I appreciate your understanding of how audio can play a critical role in the feedback process. It is an area that providers and softwares fail to place an appropriate degree of importance on in a lot of cases. I'm hoping that auditory feedback can see more development and research to show its benefits when compared to modalities that rely solely on visual feedback or simple discrete auditory feedback. ~ Cole Preuett, @ EEGStore — eegstore.com

Feedback regarding the importance of BCMI-2's personalisable sound control parameters:

> The developed system offers great flexibility in the creation of neurofeedback applications with immediate reaction to minor changes in the underlying psychophysical processes. This can be advantageous for various implementations of neurofeedback protocols. It would be great to see further dissemination of the results, maybe via an open knowledge base for sharing NFB-training protocols and user experiences. ~ Chris Veigl, Developer @ Brainbay — brainbay.nl

> Since the whole idea of biofeedback/neurofeedback is direct and specific feedback and it is based on operant conditioning, it is quite important that the feedback (either audio or visual) is in line with that. That is the reason we also offer so many different types of feedback, certain feedback simply work better with one person than with another. Hope that helps Krisztian. ~ Representative @ Mind Media BV — mindmedia.com

6.2.2 Recommendations

To help future BCMI developers support meditation practices in NFT and artistic performance settings, based on the knowledge gained in this research, I recommend first

[2] Another way to use BCMI-2 is to take it apart and connect its parts to new software. For instance, we could develop new interactive soundscapes controlled by brain signals classified in the OpenBCI-SuperCollider Interface or develop new software to classify signals to be mapped via OSC to sound parameters in the Shamanic Soundscape Generator.

- consulting the flowchart in Fig. 6.1 to identify the specific meditation techniques, their neuromarkers, and the missing steps of the envisioned BCMI and then
- considering a list of questions and suggestions below to help design the system. This list is first organised in the order of the BCMI steps and then thematically. To indicate the significant number of potential hardware and software combinations, many of my questions are open-ended.

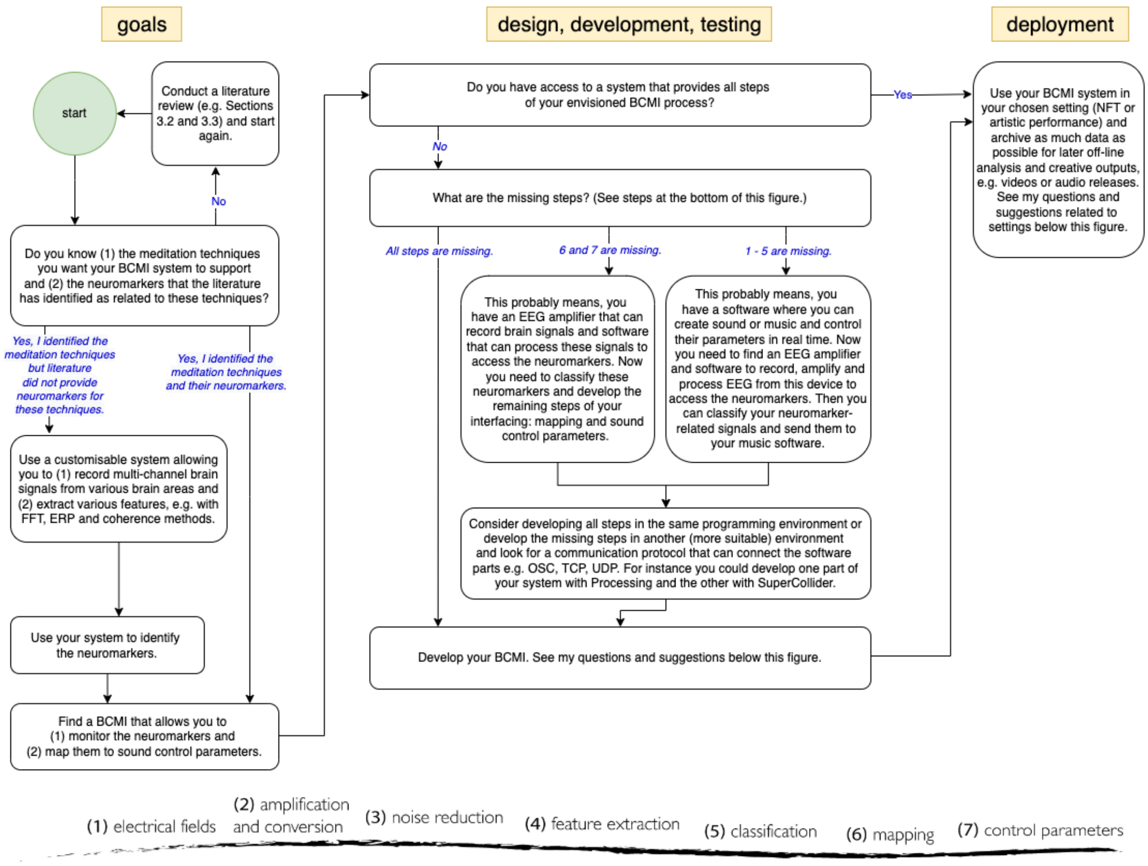

Figure 6.1: BCMI design flowchart (top) and BCI steps (bottom).

Steps (1) electrical fields and (2) amplification and conversion

- Have you reviewed the available BCI systems for your BCMI? Some EEG amplifiers might come with software you can implement in your steps (see Section 3.1 for a general introduction and references to publications comparing systems).
- Do you (or your institution) have suitable EEG hardware you can experiment with, or will you have to purchase this hardware?
- Do you need your system to acquire EEG from multiple amplifiers or only one?

Step (3) noise reduction

- What options do you have for noise reduction and impedance measurement (e.g. a standalone application or SDKs provided by the developer of your EEG amplifier or libraries/classes native to considered IDEs)? What are the advantages and disadvantages of these options?
- Have you explored machine-learning options for noise reduction?

Steps (4) feature extraction and (5) classification

- What options do you have for feature extraction (e.g. a standalone application or SDKs provided by the developer of your EEG amplifier or libraries/classes native to considered IDEs)? What are the advantages and disadvantages of these options?
- If you can access signals classified by proprietary (not open-source) algorithms, are you planning to use them?
- Have you explored the literature on feature extraction methods used in BCI (Section 3.1), NFT (Section 3.2 and 3.3) and artistic performance settings (Section 3.6)?
- Can your software application extracting the neuromaker-related features classify them and make them available for mapping? For instance,
  - can you classify your features as (programming) variables?
  - can you use a communication protocol (e.g. OSC, TCP, UDP) to send these signals to another software program?

Steps (6) mapping and (7) sound control parameters

- Do you know the setting in which you will use your system (e.g. NFT, artistic performance or both)?
- Is accuracy or aesthetics more important for your work, or are both required?
- Have you considered neurofeedback protocols
  - including or excluding sound with short or continuous feedback (Section 3.2)?
  - providing immediate or accumulative feedback (Chapter 4)?
- Have you considered employing gaming elements to increase your users' engagement (Sections 3.5.2 and 4)?
- Have you considered using spatial audio to increase the immersion of your audience (Section 3.5.2)?
- Have you reviewed the different approaches used for mapping data to sound (e.g. low- and high-level sonifications) (Section 3.7)?
- Have you explored entrainment methods that can help support your chosen meditation practice (e.g. auditory, visual entrainment, haptic or their multimodal combination) (Sections 3.2, 3.3 and 3.4)?
- If you use neurofeedback protocols, will you adjust their thresholds manually, or will your software adjust them automatically (Dhindsa et al., 2018)?

NFT and artistic performance settings

- Have you considered how users with different levels of meditation experience will interact with your system? For instance, will the music it creates be engaging — for the user or an audience — if the user cannot successfully induce and maintain a meditative state?
- Can audience members test your system at your event or perhaps be part of your performance?
- Do you plan to visualise your brain signals as well?

- Have you considered how much detail of the interfacing process you should explain to your users or audience? My advice for artistic performances is to be as transparent as possible about the interfacing process, and ask the audience to choose between engaging with the performance intuitively or analytically. For instance, I asked my audience to either meditate with me with their eyes closed or monitor how my EEG's sonification correlated with its visualisation on the screen behind me.
- Have you considered the need for assistance? While you probably do not need an additional person to conduct NFT sessions, performance settings can be much more demanding. Therefore, I advise organising support not only for setting up the technical gear but also for performing soundchecks.
- In a performance setting, do you plan to set up an entirely computer-controlled system, or will certain parts of the mapping be adjusted by a performer (e.g. the volume or spatialisation of a sonified EEG)? Do you plan to discuss the advantages and disadvantages of these two approaches to aesthetics with your audience?

Engaging with academic and public audiences can be a two-way process of giving and receiving information. During this research, I used my BCMI systems, or their parts, in artistic performances, demonstrations, workshops and other collaborative projects. I also presented my research without these systems at symposiums, conferences and other small events. People at these events gave me valuable feedback on my work, and some asked to be put on my mailing list so they could be informed about upcoming studies to participate in. These events also led to collaborative projects, enhanced my academic profile and developed my public speaking and performing skills. Therefore, I recommend that BCMI developers seek regular opportunities to disseminate their progress.

Active, passive or mutually-oriented BCMI

- What options do you have for active and passive BCI (e.g. a standalone application or SDKs provided by the developer of your EEG amplifier or libraries/classes native to considered IDEs)? What are the advantages and disadvantages of these options? For example, hard systems might be easier to develop than soft or hybrid ones, as the last two might require a good understanding of machine-learning.
- Is active, passive, or a mutually-oriented BCMI more suitable for your chosen meditation technique? Would a more conscious or spontaneous form of operant conditioning be more effective? For instance, in concentrative meditation, where users could focus consciously on one sound of a soundscape instead of the overall ambience, a hard BCI that relies on conscious operant conditioning might be more useful. However, as it is ultimately the user who decides how to pay attention and to what, this is an exciting inquiry. Krol, Andreessen and Zander (2018) discuss this issue as follows:

  > Care should be taken when presuming that mental states can be readily categorized as 'spontaneous' versus 'voluntary', as required by these definitions of BCI systems. Similarly, the activity ultimately used by any BCI system may not precisely fit one such category. A user who is aware of a passive BCI system might be influenced by the expectations they have of that system and voluntarily commit attentional resources to make sure that the 'spontaneous' activity takes place. A user might also attempt to consciously modulate this activity if results are not as expected. The other way around,

an active BCI might rely on, or inadvertently make use of, brain activity that is not fully voluntarily controlled by the user. Meditation, as an example, seems to present an ambiguous mixture of both: it is the voluntary attempt to induce a state that is usually only achieved when contextual factors align. ... the categorisation of a BCI system as (re)active or passive ultimately depends on the individual user and not on the system itself.

- Are you developing a system primarily for yourself or for others, and if for others, what technical skills are required to operate the system?
- Have you considered the scalability of your system? For instance, if you are building a minimum viable product – a proof-of-concept tool, as I did in this research – will it have a stable framework with clear code for you (or others) to expand on?
- Have you considered ethics-related issues when recording others' EEG signals (e.g. will you ensure that participants' data is stored safely)?

Technical and artistic skills

At the start of a BCMI project, you might have either primarily artistic or primarily technical skills. However, developing a BCMI requires both, so I advise finding resources that can help further develop the skills you lack. For instance:

- What expertise in music, BCI, or BCMI can your co-researchers, collaborators, and supervisors contribute to complement your own skillset?
- How can you develop relationships with individual researchers or research communities that have mastered these skills? For instance:
  - Do you know the key researchers in the field of BCMI? (see Section 3.6)
  - Do you have the writing skills to summarise your issue clearly and succinctly via direct email or internet forums?
  - Are you aware of relevant events where you can demonstrate and discuss your progress (e.g. NIME, ICAD, eNTERFACE and NFT events)?

Terminology, APM, personal development and creative outputs

Due to the interdisciplinary nature of BCMI research, some of its terminologies are not always used consistently across the literature. In Section 3.6.4, I briefly discuss this issue, specifically in relation to the terms 'sonification', 'musification' and 'control'. I also encountered it with other terms in various domains in my literature review. While experienced researchers of interdisciplinary studies are aware of this inconsistency and of the fact that definitions evolve over time, a novice researcher could become troubled by it (especially if English is not their first language). Therefore, I advise using or designing a note-taking system that can help you stay on top of this from the start of the research onwards.

For me, using APM as the overall research methodology was helpful. Therefore, I suggest considering it for other projects seeking to develop BCMI. Contrary to traditional waterfall-style management, in which the methods and literature review are established initially and not adjusted during the research, APM's approach feels more natural. Its flexibility allowed overlapping projects to inform each other and emerging questions and methods to adapt to the course of the project's development. However, as this flexibility could also be misused (e.g. by allowing too much time to address non-priority issues), I advise regular meetings with co-developers, stakeholders or supervisors to help monitor progress.

As we likely create meditation tools because we want to improve our own meditation practices, we can utilise the testing stages for our personal and spiritual development in actual mediation sessions.

I also advise considering the production of creative outputs during the process (e.g. audio releases or video documentation of performances) to help embody the richness of the research and expand its scope across and beyond disciplinary borders.

By considering these recommendations, I hope others can streamline their BCMI developments to support meditation in NFT and artistic performance settings. I am happy to provide further insights if needed.

6.3 New Goals

One of my new goals is to start addressing the new objectives of the BCMI-2 project (Chapter 5). Regarding the OpenBCI-SuperCollider Interface part of the BCMI-2 system (Section 5.2), first, I plan to (1) program an automatic neurofeedback threshold calculation to help adjust the difficulty levels of the operant conditioning in NFT sessions, (2) add a heart-rate monitor to provide more comprehensive biofeedback and more data for later analysis and to (3) investigate the potential use of the FEELTRACE instrument for recording users' perceived emotions during sessions. Regarding the Shamanic Soundscape Generator part of the system (Section 5.3), first, I plan to (1) program customisable options for accumulative neurofeedback based on the BCMI-1 neurogame (Chapter 4), (2) add extra drum tracks to help experiment with polyrhythmic patterns and to (3) incorporate the use of the Ambisonic Toolkit as an alternative to my current surround spatialization method. Furthermore, I will invite researchers with advanced programming skills to contribute new feature extraction methods and sound control parameters to BCMI-2 via the projects' GitHub repositories. Regarding the use of BCMI-2, my first goal is to carry on supporting my own meditation practice with the system to eventually be able to demonstrate a breakthrough into an ASC during a live artistic performance.[3] The second goal is to conduct new NFT sessions with more participants in randomised, placebo-controlled, double-blind studies to help compare the effectiveness of different neurofeedback protocols and ARE parameters in inducing and maintaining different meditative states.

To attract the attention of academic and non-academic researchers for collaborations, I plan to build a website that hosts the system's documentation with concise video tutorials and shares code, music

[3] The new neurofeedback protocol I have been developing for this artistic setting is based on Flor-Henry, Shapiro and Sombrun (2017) demonstrating neuromarkers of SSC. This protocol and other ongoing projects stemming from this research are outlined in Appendix 5.

and experiences with the community of interest. In line with De la Hera Conde-Pumpido's (2017) recommendations linked to social aspects of persuasive games (Section 3.5.1), this website shall help guide and foster conversations to establish relationships between users and developers. To gain attention, I also plan to start a podcast where artists and researchers can discuss BCMI and organise a symposium at the University of Essex. Finally, I will continue discussing funding applications with academic researchers and relevant industries to gain financial support for these new goals.

Chapter 7

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Chapter 8

Appendices

Overview:

Appx.1. Complete List of Creative Outputs

Appx.2. BCMI-2 BCMI Data File Examples

Appx.3. BCMI-2 NFT Session Files (GitHub repository)

Appx.4. BCMI-2 Listening Study Files (GitHub repository)

Appx.5. Ongoing Work Summary

Appx.6. Various Feedback

8.1 Appx.1 Complete List of Creative Outputs

date	name	location	category	audience	intended audiences	updated data (04/08/22)	URL
02-Jan-16	Compulsive Music Waves I.	BandCamp (internet)	audio release	played: 20 completed plays (BandCamp Stats) + YouTube views	people listening to electronic music and interested in using SuperCollider for live performance	BandCamp stats (see under audience column)	https://tedor.bandcamp.com/album/compulsive-music-waves-i
18-Jan-16	Developing Neuro-feedback Music Software for Academic Stress Management and Well-being	MPA PhD Seminar, CIMTR, ARU, Cambridge	event (presentation)	20	music and performing arts researchers	informal feedback	https://bcmi.khofstadter.com/music-therapy-clinic-talk-2016/
18-Jan-16	Developing Brain Computer Music Interfacing Software	Sonic Art Students, Music Department, ARU, Cambridge	event (demonstration)	17	people interested in sonic art	informal feedback	https://bcmi.khofstadter.com/sonic-art-guest-talk/
23-Mar-16	Developing Brain Computer Music Interfacing Software (progress)	MPA PhD Seminar, CIMTR, ARU, Cambridge	event (presentation)	19	music and performing arts researchers	informal feedback	
24-May-16	Compulsive Music Waves / Deciphering Addictions	Pint of Science Festival, St Barnabas Church, Cambridge	event (installation)	viewing at presentation: 60 installation: 50	people interested in addictions e.g. compulsive disorders	informal feedback	https://bcmi.khofstadter.com/pint-of-science-installation/
06-Jun-16	Brain Computer Music Interfacing for Stress Management	ARU Research Conference, ARU, Chelmsford	event (poster)	100	researchers	informal feedback	https://bcmi.khofstadter.com/ARU-research-conference-poster/
21-Jun-16	Brain Computer Music Interfacing Software Development for Well-being (SM?)	MPA PhD Seminar, CIMTR, ARU, Cambridge	event (presentation)	18	music and performing arts researchers	informal feedback	https://bcmi.khofstadter.com/MPA-seminar-talk/
14-Jul-16	Brain Computer Music Interfacing Software Development for Well-being	Musedelica Symposium, University of Sussex, Brighton	event (demonstration)	25	people interested in psychedelic music	informal feedback and feedback from organiser (see in later part of appendix)	https://bcmi.khofstadter.com/musedelica-symposium-demo/
17-Jan-17	Brain Computer Music Interfacing Software Development for Well-being (progress)	MPA PhD Seminar, CIMTR, ARU, Cambridge	event (presentation)	20	music and performing arts	informal feedback	
17-	Focus Neurogame for	Clip Sound, Firstsite	event	16	music and performing arts, sensor	informal feedback and written	https://bcmi.khofstadter.com/

date	name	location	category	audience	intended audiences	data collection undertaken (05/03/21)	URL
Jan-17	Meditation and Performance	Museum and Gallery, Colchester	(demonstration)		technology, human computer interfacing	feedback from organiser (see in later part of appendix)	firstsite-clip-sound-demo/
03-Jan-18	Compulsive Music Waves II.	BandCamp (internet)	audio release	Played: 4 complete plays (BandCamp Stats)	people interested in listening to music to help focus	BandCamp stats (see under audience column)	https://tedor.bandcamp.com/album/compulsive-music-waves-ii
01-Feb-18	NeuroSky-SuperCollider Interface	GitHub (internet)	open-source software	published, waiting to be tested by others	creative technologists, neurofeedback practitioners, neurogamers, meditators	informal feedback (used at 17/01/2017 event)	https://bcmi.khofstadter.com/neurosky-supercollider-interface-and-audio-neurogame/
14-Feb-18	A Brain-Computer Music Software Interface (BCMI) for Mindfulness	Multilingual Conference, University of Essex, Colchester	event (presentation)	45	general public	informal feedback and written feedback from organiser (see in later part of appendix)	https://bcmi.khofstadter.com/multilingual-conference-demo/
24-Feb-18	IBVA-SuperCollider Interface	GitHub (internet)	open-source software	published, waiting to be tested by others	creative technologists, neurofeedback practitioners, neurogamers, meditators	n/a	https://bcmi.khofstadter.com/ibva-supercollider-interface/
14-Mar-18	A Brain-Computer Music Software Interface (BCMI) for Mindfulness	StoryLab Symposium, CIMTR, ARU, Cambridge	event (presentation)	25	researchers	informal feedback + visual 'interpretation of my presentation'	https://bcmi.khofstadter.com/storylab-symposium-talk/
18-Apr-18	Brain Computer Music Interfacing for Meditation	Qujing University, Yunnan, China	event (presentation)	70	general public, MA students and academic staff	informal feedback	https://bcmi.khofstadter.com/qujing-university-talk/
18-May-18	Brain Computer Music Interfacing for Meditation	CIMTR Networking Event, ARU, Cambridge	event (presentation)	30	people interested in arts, health and wellbeing	informal feedback	https://bcmi.khofstadter.com/cimtr-networking-event/
24-Oct-18	Brain Computer Music Interfacing for Meditation (The Archive and the Contested Landscape)	2018 Festival of Ideas, ARU, Cambridge	event (presentation)	30	people interested in arts, soundscapes and the intersection of art and geology	informal feedback	https://bcmi.khofstadter.com/festival-of-ideas-2018-talk/
21-Nov-18	Tibetan Singing Bowl Meditation	ARU, Cambridge	study	5 (participants and film crew)	people interested in sound therapy, meditation, brainwave measurements	informal feedback and feedback from film director (see in later part of appendix)	https://bcmi.khofstadter.com/tibetan-singing-bowls-meditation-with-eeg/
28-Nov-18	ASMR Experiment	ARU, Cambridge	study	10 + film shown at BBI London Film Festival	sound therapy, meditation, brainwave measurements, ASMR	informal feedback and feedback from film director (see in later part of appendix)	https://bcmi.khofstadter.com/asmr-eeg-tests/
27-Feb-19	Demonstration of Brain-Computer Music Interfacing Soundscape - Generative Rhythmic Entrainment	AES Internation Conference on Immersive and Interactive Audio, York	event (demonstration)	40	people interested in immersive and interactive audio	informal feedback	https://bcmi.khofstadter.com/aes-york-conference-demo-2019/
13-Jun-19	Aphorisms by David Ryan	ARU, Cambridge	event (performance)	50	people interested in collaborative art performances	informal feedback	https://bcmi.khofstadter.com/aphorisms/
20-Sep-19	Neurofeedback Sessions	Colchester	study	2 (trainees: b and m)	participants novice meditators	detailed surveys from 2x3 sessions and EEG data	https://bcmi.khofstadter.com/neuromeditation-sessions/

date	name	location	category	audience	intended audiences	data collection undertaken (05/03/21)	URL
26-Oct-19	NeuroMeditation with Music (Talk and a BCMI performance)	2019 Festival of Ideas, ARU, Cambridge	event (demonstration)	64	people interested in meditation, rhythmic entrainment, sonic driving, neurofeedback, shamanic journeying, altered states of mind, surround sound, neuromeditation	informal feedback, some written feedback	https://bcmi.khofstadter.com/festival-of-ideas-2019-talk-performance/
06-Nov-19	NeuroMeditation with Music (Talk and a BCMI performance)	Music Department, ARU, Cambridge	event (demonstration)	22	people interested in meditation, rhythmic entrainment, sonic driving, neurofeedback, shamanic journeying, altered states of mind, surround sound, neuromeditation	informal feedback	
14-Nov-19	Listening Study 1 (Testing Rhythmic Entrainment)	GitHub (internet)	study	84 (completed Survey Monkey)	people interested in meditation, rhythmic entrainment, sonic driving, neurofeedback, shamanic journeying, altered states of mind	detailed survey responses (n=84)	https://bcmi.khofstadter.com/listening-test-survey-1/
22-Feb-20	Shamanic Soundscape – NeuroFeedback Sessions	BandCamp (internet)	audio release	Played: 60 completed plays; purchased: 3 (BandCamp Stats)	people interested in meditation, rhythmic entrainment, sonic driving, neurofeedback, shamanic journeying, altered states of mind	BandCamp stats (see under audience column)	https://tedor.bandcamp.com/album/shamanic-soundscape-neurofeedback-sessions
23-Mar-20	Shamanic Soundscape – Level Two	BandCamp (internet)	audio release	Played: 690 completed plays; purchased: 9 (BandCamp Stats) + Youtube views: 2,515	people interested in meditation, rhythmic entrainment, sonic driving, neurofeedback, shamanic journeying, altered states of mind, surround sound, binaural beats	used in Listen Study 1 (n=84) and Listening Study 2 (n=24)	https://tedor.bandcamp.com/album/shamanic-soundscape-level-two
24-Mar-20	OpenBCI-SuperCollider Interface	GitHub (internet)	open-source software	published, waiting to be tested by others	creative technologists, neurofeedback practitioners, meditators	used in two projects (1 - neurofeedback sessions (n=3) and at performance at Festival of Ideas 2019 (n=60, with only a few written feedback, informal feedback on video)	https://bcmi.khofstadter.com/openbci-supercollider-interface/
24-Mar-20	Shamanic Soundscape Generator	GitHub (internet)	open-source software	published, waiting to be tested by others	creative technologists, neurofeedback practitioners, meditators	used in two projects (1 - neurofeedback sessions (n=3) and at performance at Festival of Ideas 2019 (n=60, with only a few written feedback, informal feedback on video)	https://github.com/krisztian-hofstadter-tedor/bcmi-sc01-shamanic-soundscape-generator
14-Jun-20	Brain Computer Music Interfacing for Meditation 2	2020 ARU Talking Science, Online presentation, ARU, Cambridge	event (presentation)	50 (Google Analytics)	people interested in meditation, rhythmic entrainment, sonic driving, neurofeedback, shamanic journeying, altered states of mind	website analytics (see under audience column)	https://bcmi.khofstadter.com/aru-talking-science-series-2020/
01-Sep-21	Blue Forest	Colchester	project (ongoing)	1 collaborator: Lucas Hofstadter-Wu	audio visual storytelling, childcare, meditation, visualisation, altered states of mind	diary, audio recordings and drawings	https://bcmi.khofstadter.com/blue-forest/
01-Sep-21	Other (Ongoing) EEG Studies	Colchester	project (ongoing)	1 collaborator: Andrej Hrvatin, David Ryan, Fredrik Olofsson	meditation, visualisation, altered states of mind, binaural beats, hemisphere synchronisation	diary and EEG recordings	https://bcmi.khofstadter.com/further-eeg-studies/

8.2 Appx.2 BCMI Data File Examples

Example 1
(raw, accelerometer and timestamps)

index	ch1raw	ch2raw	ch3raw	ch4raw	ch5raw	ch6raw	ch7raw	ch8raw	accel1	accel2	accel3	timestamp1	timestamp2
251	6667.19	3531.78	-187500.02	-187500.02	-187500.02	-187500.02	-187500.02	-187500.02	-0.018	-0.142	0.994	16:25:34.768	1563290734768
252	6645.96	3543.15	-187500.02	-187500.02	-187500.02	-187500.02	-187500.02	-187500.02	-0.018	-0.142	0.994	16:25:34.776	1563290734776
253	6652.59	3587.66	-187500.02	-187500.02	-187500.02	-187500.02	-187500.02	-187500.02	-0.018	-0.142	0.994	16:25:34.776	1563290734776
254	6677.87	3601.09	-187500.02	-187500.02	-187500.02	-187500.02	-187500.02	-187500.02	-0.018	-0.142	0.994	16:25:34.795	1563290734795
255	6685.81	3566.58	-187500.02	-187500.02	-187500.02	-187500.02	-187500.02	-187500.02	-0.018	-0.142	0.994	16:25:34.795	1563290734795
0	6665.54	3529.72	-187500.02	-187500.02	-187500.02	-187500.02	-187500.02	-187500.02	-0.018	-0.142	0.994	16:25:34.796	1563290734796
1	6644.91	3541.32	-187500.02	-187500.02	-187500.02	-187500.02	-187500.02	-187500.02	-0.018	-0.142	0.994	16:25:34.797	1563290734797
2	6650.49	3584.55	-187500.02	-187500.02	-187500.02	-187500.02	-187500.02	-187500.02	-0.018	-0.142	0.994	16:25:34.798	1563290734798
3	6675.62	3595.77	-187500.02	-187500.02	-187500.02	-187500.02	-187500.02	-187500.02	-0.018	-0.142	0.994	16:25:34.799	1563290734799

Example 2
(raw, accelerometer and timestamps)

index	ch1raw	ch2raw	ch3raw	ch4raw	ch5raw	ch6raw	ch7raw	ch8raw	accel1	accel2	accel3	thetaFz	gammaPz	level	timer1	timer2	timer3	timer4	timestamp1	timestamp2
248	-5606.4	-11322.88	6368.46	2716.23	9030.89	-5201.14	-6278.47	8870.4	0.006	0.014	-1.002	1.4	2	10	29	2	0	0	11:07:45.587	1569492465587
249	-5561.09	-11251.82	6426.48	2766.1	9083.99	-5149.33	-6202.72	8926.66	0.006	0.014	-1.002	1.4	2	10	29	2	0	0	11:07:45.587	1569492465587
250	-5526.09	-11202.85	6467.79	2818.0	9126.69	-5103.6	-6151.89	8964.17	0.006	0.014	-1.002	1.4	2	10	29	2	0	0	11:07:45.587	1569492465587
251	-5536.44	-11220.37	6450.96	2808.68	9115.51	-5112.72	-6171.99	8950.73	0.006	0.014	-1.002	1.4	2	10	29	2	0	0	11:07:45.587	1569492465587
252	-5596.65	-11307.86	6375.32	2735.36	9044.86	-5184.82	-6261.48	8883.05	0.006	0.014	-1.002	1.4	2	10	29	2	0	0	11:07:45.587	1569492465587
253	-5606.96	-11325.45	6365.62	2716.34	9029.03	-5203.37	-6276.66	8867.85	0.006	0.014	-1.002	1.4	2	10	29	2	0	0	11:07:45.587	1569492465587
254	-5555.77	-11255.09	6430.8	2774.41	9088.82	-5145.39	-6199.14	8920.27	0.006	0.014	-1.002	1.4	2	10	29	2	0	0	11:07:45.587	1569492465587
255	-5520.3	-11203.5	6475.88	2822.87	9135.36	-5098.46	-6143.91	8959.81	0.006	0.014	-1.002	1.4	2	10	29	2	0	0	11:07:45.588	1569492465588
0	-5532.55	-11220.22	6457.11	2811.02	9123.27	-5108.76	-6164.43	8947.92	0.006	0.018	-1.0	1.4	2	10	29	2	0	0	11:07:45.588	1569492465588
1	-5592.16	-11309.13	6382.07	2740.3	9054.13	-5179.35	-6256.07	8877.51	0.006	0.018	-1.0	1.4	2	10	29	2	0	0	11:07:45.595	1569492465595

8.3 Appx.3 Neurofeedback Sessions Files

A GitHub folder with NFT session files including, consent forms, questionnaires in Chinese/English, raw analysis in spreadsheets, BCMI data file analysis in plots and text, notes, etc.:

https://github.com/krisztian-hofstadter-tedor/bcmi-2-3-nf-sessions-appendix

- `\b` (3 NF sessions: consent form, filled in questionnaires, notes, plots)
- `\m` (same as `\b`)
- `questionnaire-en.md` (questionnaire in Chinese)
- `questionnaire-zh.pdf` (questionnaire in English)
- `questionnaires-answers-summary-en.xls` (answered questionnaire summery with pre-analysis in sheets)
- `supercollider-plotting-code.scd` (SuperCollider code for plotting BCMI data)

The participants gave consent for their data to be public. Their raw EEG is not public.

8.4 Appx.4 Listening Studies Files

A public GitHub repository containing data for both listening studies:

https://github.com/krisztian-hofstadter-tedor/bcmi_2-listening-studies

Folders include detailed information on the four stages of the studies:

1. survey design e.g. the surveys in different formats and supporting assets
2. call (advertising) e.g. list dissemination channels
3. gathered data e.g. anonymised responses in raw .csv format
4. some analysis including the automatic evaluations provided by SurveyMonkey and some examples of my visual analysis with RAWGraphs v.1 in raw .svg formats.

The graphs using these .svg files were post-edited in Adobe Illustrator. The raw survey data is publicly available (open access) firstly as it was a requirement by one of the Facebook groups where the call was advertised, and secondly, to provide data for researchers interested in meditation, visualisation, shamanism and auditory entrainment.

8.5 Appx.5 Ongoing Projects

8.5.1 Blue Forest

Blue Forest is a project-based learning environment. It is an imaginary forest my (now) 5-year-old son and I have been developing. It all started with me drumming after his bedtime stories to help him fall asleep. After a few days, I noticed that drumming along did not capture all his attention; therefore, I began devising a story in which process he became more and more involved. We created characters and places to visit within this forest. We have colourful foxes who open the forest gates, a blue rabbit whose house moves to a different location within the woods every time we visit and many other remarkable creatures. We also have some visiting characters from parallel stories we encounter in books or video animations (e.g. Blaze and the Monster Machines by Nickelodeon Animation Studio and Totoro by Studio Ghibli). Between January 2019 and today, I have archived dozens of audio files capturing our voices and the drumming, as well as drawings of the characters and maps of the ever-changing forest. Today, the project has not only helped him fall asleep easier but also bond with me while learning about drawing, writing, making music, storytelling and meditation.

8.5.2 Follow-up listening study with M

As mentioned in Chapter 5, due to the COVID-19 pandemic, participant M could not travel to the UK; therefore, I am designing a follow-up study with her that does not involve the BCMI-2 system but only listening to non-interactive soundscapes.

8.5.3 Book chapter on contemporary entheogenic healing

I am extending my knowledge on how auditory entrainment has been used in shamanic practices without psychedelics. I aim to summarise the outcomes of this process in a chapter of a handbook on the cross-cultural assessment of how we could revitalise the ancient techniques of shamanic traditions for contemporary healing practices.

8.5.4 Other BCMI projects

Besides the NFT and performance settings (Chapters 4.4 and 4.5), I use the OpenBCI-SuperCollider Interface in other projects, sometimes simply to record EEG while listening to music and sometimes to control sound. The first three projects below do not have interactive sound, while the last three do.

8.5.4.1 MONOLIT

In this project, I investigate how MONOLIT (Hrvatin, 2019), an hour-long drone composition, can help one enter an ASC. Before listening to the piece, I follow the composer's breathing techniques. I record my EEG before breath-work, during breath-work and the listening part, and for a short time after the listening part. So far, several of my experiments when listening to MONOLIT have evoked visual imagery similar to the imagery I see when using the shamanic soundscapes discussed in Chapter 5.7. As with the shamanic soundscape projects, visions are archived into drawings and voice recordings after listening and later used for analysis. I have been in touch with the composer since his help with fine-tuning my drumming techniques for shamanic journeying.

8.5.4.2 The Gateway Experience

In this project, I investigate how the binaural beats of 'The Gateway Experience' could help induce an ASC (Monroe Institute, 1962a). Designed by Robert Monroe, a pioneer of brainwave entrainment, the Gateway Experience has been referenced in research on binaural beats for decades. Here too, I measure my EEG before, during and after the listening parts and interpret visions in drawings for later analysis.

8.5.4.3 Shamanic journeying and drumming

Out of all methods experienced in this research, simply drumming on my frame drum alone has been the most effective in inducing the flashing visual imagery and then, about 15 minutes later, merging them into one continuous visual narrative — the journey. I experience this merge as the breakthrough in my meditation. Being able to express my inner experience with tempo and rhythmic changes seems to subdue the desire to interpret the experience analytically. Here too, EEG is measured before, during and after the sessions, as well as drawings made to help interpret the experience.

8.5.4.4 Corine protocol

In this project, I have been designing a new neurofeedback protocol for artistic performance purposes. The protocol is based on the paper by Flor-Henry, Shapiro and Sombrun (2017) titled 'Brain changes during a shamanic trance: Altered modes of consciousness, hemispheric laterality, and systemic psychobiology', in which they analysed a shamanic practitioner's EEG with qEEG and LORETA methods while she was entering an SSC. As the number of channels used in their project is much higher (43) than what I currently can measure (8), the classified brain signals for my Corine protocol are simplified. These simplifications were also needed as the BCMI-2 does presently not support LORETA feature analysis, only qEEG (Fig. 8.1).

8.5.4.5 Here and Now (revisited)

As a member of David Ryan's Opera Aperta Project I have been designing an alternative version of Ryan's recent composition, 'Here and Now'. For my revisit, I developed sound textures to use as control parameters in a BCMI soundscape and a new neurofeedback protocol that controls these textures. The textures use recordings from the original piece (e.g. bass clarinet, percussion, Tibetan bowls, cello, piano, and voices). My compositional method for this piece is similar to the one in the BCMI-2 projects: some aspects of the composition are more controlled (e.g. the overall duration). In contrast, others are more

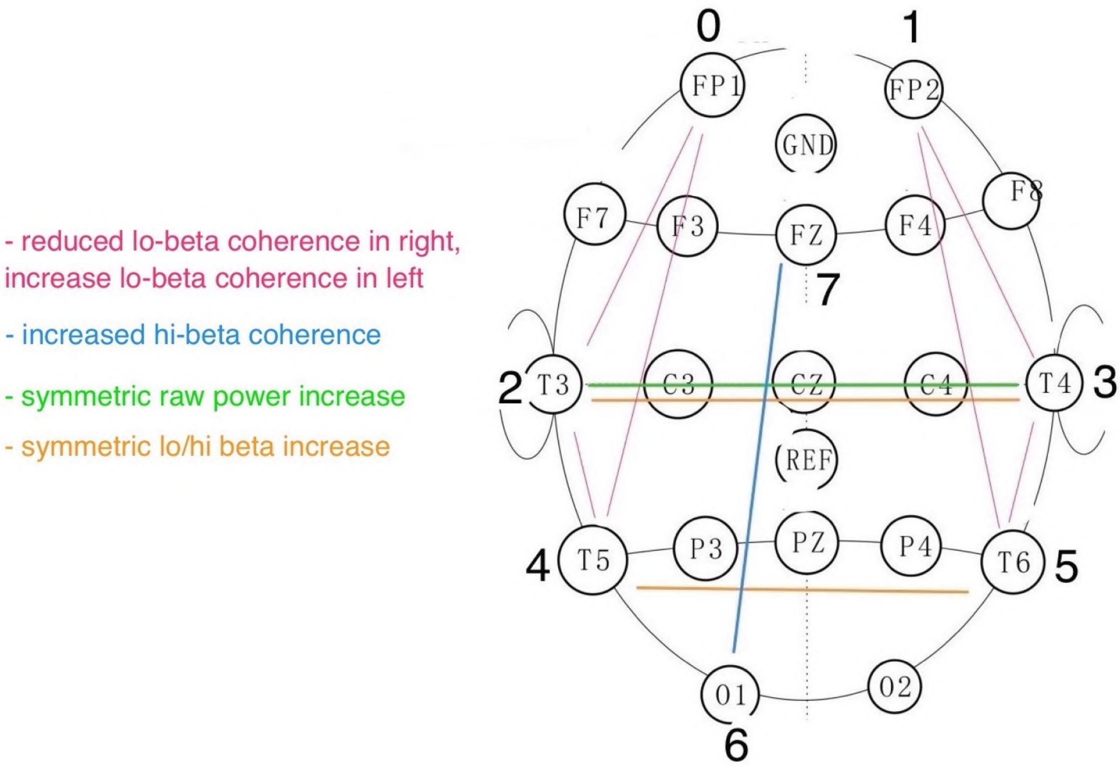

Figure 8.1: Current draft of Corine protocol with BCMI-2.

unplanned as they are mapped to classified brain signals in real-time. This project aims to demonstrate the use of BCMI for audiences primarily interested in contemporary classical music.

8.5.4.6 Berlin - Colchester BCMI

This project experiments with sending BCMI data between two countries via the internet using Tunnelblick by OpenVPN Inc. The method, developed by Fredrik Olofsson, is investigated primarily to understand how we could use the OpenBCI-SuperCollider Interface effectively in real-time BCMI performances where the performers do not share a physical space. While this project felt more relevant in the 2019-20 COVID-19 pandemic, we think it is still worth exploring.

8.6 Appx.6 Various Feedback

14 Jul 2016, Brain Computer Music Interfacing Software Development for Well-being, Musedelica Symposium, University of Sussex, Brighton

https://bcmi.khofstadter.com/musedelica-symposium-demo/

Feedback from event organiser:

1. Was my presentation aligned to your symposium?

   Yes, your talk covered some key discussion points in psychedelic music, like entrainment and trancing. It's also important to include non-drug induced ASCs when talking about psychedelic music as the connection is sometime overlooked.

2. Did you find it interesting to hear about how brain-computer music interfacing (BCMI) can be used for altering the state of mind?

   Yes indeed – it was great to have a more technical outlook included in the programme.

3. Do you think BCMI could help people make better (psychedelic) music e.g. by helping composers understand how different aspects of music (tempo, density, ...) are aligned to different changes in the brain?

   Yes, it seems like a good tool to use in experimental settings, to isolate and measure the effects of different psychedelic characteristics.

4. Would you be interested in another presentation where I could outline my most up to date research outcomes related to my art practice linked to BCMI and meditation?

   Definitely - whenever I manage to hold another conference/symposium, that is. ~**Gemma Farrell**

17 Jan 2017, Demonstration at Clip Sound, Firstsite Museum and Gallery, Colchester, UK

https://bcmi.khofstadter.com/firstsite-clip-sound-demo/

Demonstrating the prototype of the NeuroSky-SuperCollider Interface.

> The interface was a fascinating way of composing music. At CLIP we strive to find new ways of making composition and performance more accessible, removing the fear of getting it wrong and encouraging young people to take creative risks. The interface was a really powerful of doing this, taking the virtuoso element away from performing music and making it playful instead. I could definitely imagine CLIP using the interface in the future, as a way of augmenting a performer to control parameters of another instrument perhaps, or to offer interesting audience participation within a performance too. Brain interfacing offers a fascinating opportunity for tapping into creativity for musicians of all abilities. Most physical musical controllers try to take advantage of human motor skills which can be incredibly restrictive for some. It would be fantastic to welcome you back to CLIP. We are currently meeting online so we could welcome you to our online sessions, or alternatively wait until our face-to-face sessions are back and try it out first hand too. ~**Frazer Merrick**, co-founder of CLIP, Colchester, UK (Improvising. Sonic Experiments. Performances https://www.clipsoundandmusic.uk/)

01 Feb 2018, NeuroSky-SuperCollider Interface

https://bcmi.khofstadter.com/neurosky-supercollider-interface-and-audio-neurogame/

Casual testing of the interface.

> Very interesting project! I find it fascinating that I can control sounds with my brainwaves. The headset is very easy to put on my head and not uncomfortable at all. However, it does not seem to be easy to control the sounds. It was very useful that Krisztian explained what I should do to hear how certain parts of the sounds change. Relaxing the mind is not really easy, so I think there could be many people interested in doing meditation with a system that guides them with music. Cool! ~**Antonia**, Cambridge

> I believe many people can benefit from a science-driven meditation experience, especially people with mental health. But, it is not for everyone. During the meditation with the system, I felt like my state of mind was shifting, mostly receiving positive emotions but sometimes negatives too. After the session I felt relaxed, also my mood was better throughout the whole day. I like the idea of eyes closed meditation so a system like this is good because feedback comes from audio. I think your work, Krisztian is great, I believe you can help many people. In regard to other types of music to be connected to my brain, I would also enjoy goa trance without vocals! ~**Zsolt**, Cambridge

14 Feb 2018, Demonstration at Multilingual Conference, Essex, University of Essex, Colchester, UK

https://bcmi.khofstadter.com/multilingual-conference-demo/

Short presentation including EEG demonstration with IBVA and NeuroSky hardware.

> Krisztian's speech was very well received by students, staff and conference participants. It was informative and full of academic insights. Some of the academic language could be slightly difficult for beginner's to understand completely but Krisztian tried his best in tailoring his language to the public presentation. I found the brain-computer music interfacing interesting especially with Krisztian's demonstration. Meditation can improve the ability to focus and prioritise our tasks. It is an important part of mindfulness. Students, especially research students or even SEN students, could be very interested in having a meditation workshop run by Krisztian to help streamline their work. ~**Nan Zhao**, event organiser and senior lecturer at University of Essex

Oct - Nov 2018, ASMR and Tibetan Singing Bowl Meditation Experiment

Tertiary Sound: ASMR Documentary (2019) Anglia Ruskin University, AHSS

Cambridge School of Creative Industries Film and TV Production Course

Collaborator: Krisztian Hofstadter (researcher, interviewee)

Dates of Collaboration: October-December 2018

> I have worked with Krisztian Hofstadter in autumn-winter of 2018 on one of my university film projects "Tertiary Sound: ASMR Documentary". The film since proceeded to win RTS Awards for Best Sound and best Factual Film and screened at 2019 BFI London Film Festival. Krisztian joined our project as a researcher and agreed to conduct EEG readings to determine which effects ASMR sounds have on human body. Together with Krisztian, we have done one experiment in which a participant was listening to a set of Tibetan Singing Bowls and another one in which six participants were listening to ASMR sounds only. Both were recorded and read with different sets of EEG monitor systems. Krisztian provided us with an invaluable advice and guidance along the process. These experiments resulted in a necessary for us data and excellent footage that we have used in our documentary that allowed us to visualise and explain our ideas. We valued Krisztian's opinions that he has given us during the interviews and the detailed commentary he provided for us after the EEG readings and although not all of it was featured in our documentary, we found it useful for our research purposes as it drew us closer to understanding ASMR, sound and human body in general. Krisztian has brought a different perspective on ASMR to our project since he has worked in a field related to sound and was conducting his own research on brain- computer interfacing work on linking meditation. It was important for us to see that Krisztian was genuinely interested and curious about the topic of our documentary and we were able to see how ASMR was connected with his other research. For the purposes of our documentary we did not need to do further research or publish the data we have gathered, however in the future we would be interested to continue working with Krisztian and explore the effects of ASMR in a more in-depth and regulated research. We are always open to a collaboration with Krisztian on any of his projects related to this field. ~**Solomia Dzhurovska** (osolomia.wordpress.com)