2016

BRAIN-COMPUTER MUSIC INTERFACING: DESIGNING PRACTICAL SYSTEMS FOR CREATIVE APPLICATIONS

Eaton, Joel

http://hdl.handle.net/10026.1/5221

http://dx.doi.org/10.24382/4875
Plymouth University

BRAIN-COMPUTER MUSIC INTERFACING: DESIGNING PRACTICAL SYSTEMS FOR CREATIVE APPLICATIONS

by

JOEL EATON

A thesis submitted to Plymouth University in partial fulfilment for the degree of

DOCTOR OF PHILOSOPHY

Faculty of Arts

September 2015

Abstract

BRAIN-COMPUTER MUSIC INTERFACING: DESIGNING PRACTICAL SYSTEMS FOR CREATIVE APPLICATIONS

Joel Eaton

Brain-computer music interfacing (BCMI) presents a novel approach to music making, as it requires only the brainwaves of a user to control musical parameters. This presents immediate benefits for users with motor disabilities that may otherwise prevent them from engaging in traditional musical activities such as composition, performance or collaboration with other musicians. BCMI systems with active control, where a user can make cognitive choices that are detected within brain signals, provide a platform for developing new approaches towards accomplishing these activities. BCMI systems that use passive control present an interesting alternate to active control, where control over music is accomplished by harnessing brainwave patterns that are associated with subconscious mental states. Recent developments in brainwave measuring technologies, in particular electroencephalography (EEG), have made brainwave interaction with computer systems more affordable and accessible and the time is ripe for research into the potential such technologies can offer for creative applications for users of all abilities.

This thesis presents an account of BCMI development that investigates methods of active, passive and hybrid (multiple control methods) control that include control over electronic music, acoustic instrumental music, multi-brain systems and combining methods of brainwave control.

In practice there are many obstacles associated with detecting useful brainwave signals, in particular when scaling systems otherwise designed for medical studies for use outside of laboratory settings. Two key areas are addressed throughout this thesis. Firstly, improving the accuracy of meaningful brain signal detection in BCMI, and secondly, exploring the

creativity available in user control through ways in which brainwaves can be mapped to musical features.

Six BCMIs are presented in this thesis, each with the objective of exploring a unique aspect of user control. Four of these systems are designed for live BCMI concert performance, one evaluates a proof-of-concept through end-user testing and one is designed as a musical composition tool.

The thesis begins by exploring the field of brainwave detection and control and identifies the steady-state visually evoked potential (SSVEP) method of eliciting brainwave control as a suitable technique for use in BCMI. In an attempt to improve signal accuracy of the SSVEP technique a new modular hardware unit is presented that provides accurate SSVEP stimuli, suitable for live music performance. Experimental data confirms the performance of the unit in tests across three different EEG hardware platforms. Results across 11 users indicate that a mean accuracy of 96% and an average response time of 3.88 seconds are attainable with the system. These results contribute to the development of the BCMI for *Activating Memory,* a multi-user system. Once a stable SSVEP platform is developed, control is extended through the integration of two more brainwave control techniques: affective (emotional) state detection and motor imagery response. In order to ascertain the suitability of the former an experiment confirms the accuracy of EEG when measuring affective states in response to music in a pilot study.

This thesis demonstrates how a range of brainwave detection methods can be used for creative control in musical applications. Video and audio excerpts of BCMI pieces are also included in the Appendices.

Table of contents

List of publications

The research outlined in this thesis has been presented in a number of peer-reviewed papers throughout the duration of the project. They are listed here:

Miranda, E., Eaton, J., *Music Neurotechnology: a natural progression*. Ashgate Companion to Electronic Music. Ashgate, UK. Emmerson, Simon (Eds.) (Awaiting publication, 2016)

Eaton, J., Williams, D., Miranda, E., *The Space Between Us: Evaluating a Multi-user Affective Brain-Computer Music Interface.* Brain-Computer Interfaces: Vol. 2, Arts and Brain-Computer Interfaces (BCIs), pp. 103-116. D.O.I 10.1080/2326263X.2015.1101922

Eaton, J., Miranda, E., 2014. *On Mapping EEG Information into Music.* in *Guide to Brain-Computer Music Interfacing*. Springer, XVIII, 313 p. 103 illus. Miranda, Eduardo Reck, Castet, Julien (Eds.)

Eaton, J., Miranda, E., 2015. *The Hybrid BCMI – Integrating Brainwave Detection Methods for Extended Control in Musical Systems.* 11th International Symposium on Computer Music Multidisciplinary Research CMMR: Music, Mind, Embodiment. Plymouth, UK.

Eaton, J., Miranda, E., 2014. *Expanding on brain control: A real-time hybrid bcmi for drum machine combining active (SSVEP) and passive (affective response) brainwave control.* 9th Conference on Interdisciplinary Musicology CIM14, Staatliches Institut für Musikforschung, Berlin, Germany.

Eaton, J., Williams, D., Miranda, E., 2014. *Affective Jukebox: A Confirmatory Study of EEG Emotional Correlates in Response to Musical Stimuli.* Joint ICMC | SMC 2014, 11th Sound and Music Conference |14th International Computer Music Conference, University of Athens, Greece.

Eaton, J., Jin, W., Miranda, E., 2014 *The Space Between Us. A live performance with musical score generated via emotional levels measured in EEG of one performer and an audience member.* New Interfaces for Musical Expression (NIME), London, UK.

Eaton, J., and Miranda, E. R., 2013. *Real-Time Brainwave Control for Live Performance*, 10th International Symposium on Computer Music Multidisciplinary Research (CMMR): Sound, Music and Motion, Marseille, France.

Eaton, J., Miranda, E., 2013. *Real-Time Notation using Brainwave Control*. Sound and Music Computing Conference 2013. Stockholm, Sweden.

Eaton, J., 2013. *Real-Time Notation and Performing with Brainwaves*. Keynote for Sight, Sound Space and Play 2013. De Montfort University, Leicester.

Eaton, J., Miranda, E., 2012. *New Approaches for Brain-Computer Music Interfacing*. Proceedings of Music of the Mind – Music, Mind Invention, University of New Jersey, USA.

List of figures

List of tables

Abbreviations

a-BCMI	Affective Brain-Computer Music Interface/Interfacing
API	Application Programming Interface
AV	Arousal and valence
BCI	Brain-Computer Interface/Interfacing
BCMI	Brain-Computer Music Interface/Interfacing
BPM	Beats per minute
CV	Control voltage
DAW	Digital Audio Workstation
EEG	Electroencephalogram
FFT	Fast Fourier Transform
*f*MRI	Functional Magnetic Resonance Imaging
GUI	Graphical User Interface
ICCMR	Interdisciplinary Centre for Computer Music Research
IP	Internet Protocol
LAN	Local Area Network
MI	Motor Imagery
MIDI	Musical Instrument Digital Interface
NR	Noise Reduction
OSC	Open Sound Control
PC	Personal Computer
Pd	Pure Data
PSD	Power Spectrum Density
RAM	Random-Access Memory
SSVEP	Steady-State Visually Evoked Potential
SNR	Signal-to-Noise Ratio
UDP	User Data Protocol
VCA	Voltage controlled amplifier
VCF	Voltage controlled filter
VJ	Visual Jockey
W-LAN	Wireless Local Area Network

Acknowledgements

At the beginning of my studies I was often warned that that undertaking a PhD could be a very isolating and lonely experience. It is fair to say that I found my experience to be quite the opposite. I have been fortunate to be part of a vibrant research group and there are a number of people without whose support, encouragement and contributions this work would not have been possible.

I would like to begin by acknowledging Doug and Alex from Drake Music, a charity devoted to developing access to music making for children with disabilities, through technology. They allowed me to sit in on their music sessions at Penrose Special School, Somerset. Their enthusiasm was infectious and the sessions provoked the initial ideas around limited movement and music participation that set me on my research path. I would also like to thank the staff at the Royal Hospital for Neuro-Disability in London, in particular Julian and Sophie, for making our work with the patients as smooth as possible. Speaking of which I would also like to thank Steve, Clive, Richard and Rosie, the four brains that made up the *ParaMusic Ensemble,* and also the Bergersen String Quartet. It was a pleasure to work with you, and if you enjoyed performing with the system even half as much as I enjoyed watching it then all the hard work was worthwhile.

I feel honoured to have been part of the *Interdisciplinary Centre for Computer Music Research* (ICCMR) research group during an exciting period and with a diverse bunch of members. Above all, the social and intellectual exploits of the team have kept me hugely entertained and sane throughout my time in Plymouth. I'd like to thank Alexis who prepared me well for a PhD by inviting me work on his insane projects, Federico for injecting some continental class to the lab (albeit never on time), Aurélien for those cold and bleak trips to watch terrible Argyle games and Ed and Ben for all the running sessions. Also to Pierre, Nuria and Michael. A special mention is required for Jared, you have been a huge source of humour for me, now get on with your PhD! I will always have fond

memories of team ICCMR's running achievements, drinking achievements but mostly just hanging out with you all.

I particularly want to thank Dr. Duncan Williams. Firstly, for his collaboration on the *Affective Jukebox*, and for being my sounding board for the last two years of my research. It is highly likely that there is a strong correlation between my research achievements and his time, and for that I am massively grateful. Thanks also for proof-reading this thesis (as well as other numerous papers) and for being a true friend. You singlehandedly made Plymouth bearable!

A few people have contributed towards the work in this thesis and in doing so have given up their own time and efforts. A big thank you to Weiwei Jin for her exquisite and unique musical mind helping make *The Space Between Us* a musical reality and her contribution to *A Stark Mind*. I am also thankful to Fiona Miller for her vocal performance in *The Space Between Us* in Berlin, December 2014. I would like to thank Pierre Largeron and Esther Coorevits for performing A Stark Mind in Plymouth, June 2015, two very talented people who are a joy to work with.

I am especially grateful to my supervisor Eduardo Miranda, who has guided me through my studies and never let me slack. He encouraged me in the early stages of my research when I really needed it, and he always believed in me throughout my years as his student. He was also a great partner to work with on our BCMI quartet project *Activating Memory*, and I thank him for his endeavour in securing me a scholarship to help me complete my studies. As such, I would like to thank Plymouth University for awarding me this scholarship. It provided me with the space and time to focus on my research, a luxury that I have never taken for granted.

I would also like to thank my family for their support over the years. I never get to see them all enough and when I do their love and kindness helps me get through anything. A

special thank you to Bethany for letting me live with her at the beginning of my studies and to my parents for all the times I've visited them to work in their warm, cosy home.

Whilst undertaking this PhD I have relocated four times, got married and am now about to be a father. All of these things have provided welcome distractions and helped me realise that a fulfilling life outside of one's studies can provide the right frame of mind needed to undertake such a project. I am also a firm, but certainly not fanatical, proponent of the belief that a healthy body can lead to a healthy mind, thus creating a sound climate for conducting research. I estimate that I have run approximately 3300 miles during my PhD studies, which has more often that not led to an exhausted (but also healthy) mind. Whether this could be taken as a metaphor for running away from my research is still up for debate, as is the sense in my decision to enter a 100K race only a matter of weeks before my final submission. Anyway, the point I wish to make here is that striving for success in a PhD has helped me strive for success in all areas of life, whatever the challenge.

Finally, I would like to thank my wife, Emily, who has been at my side throughout this entire project. She uprooted 250 miles from her friends and family to be with me whilst I pursued my research, and for that I am eternally grateful (and quite possibly eternally unforgiven). Doing a doctorate at the same time has allowed us to share something very unique, but more importantly it allowed us to spend an abundance of time together.

Collaborations

Elements of the research presented in this thesis are the result of collaborations with other researchers and practitioners whose contributions are duly acknowledged here. This reflects the range of disciplines this study encompasses.

To summarise, Professor Eduardo Miranda composed the score for *Activating Memory* (chapter 5).

The experiment presented in Chapter 6, surrounding the *Affective Jukebox* BCMI was designed and conducted with Dr. Duncan Williams, a music psychologist. Dr. Williams co-designed the experiment and jointly conducted both the trials and the data analysis. His expertise was an essential contribution to this element of the research.

Finally, the musical score for *The Space Between Us* (chapter 7) was composed with Weiwei Jin. Both an acclaimed composer and pianist, she is currently a PhD candidate at De Montfort University, UK, researching music and emotion in opera.

Finally, there were musical contributions to the performances through workshop sessions of *The Space Between Us* by the singer Fiona Miller, and to *A Stark Mind*, by both Pierre Largeron and Esther Coorevits. These are also gratefully acknowledged.

Author's Declaration

At no time during the registration for the degree of Doctor of Philosophy has the author been registered for any other University award without prior agreement of the Graduate Committee.

Work submitted for this research degree at the Plymouth University has not formed part of any other degree either at Plymouth University or at another establishment

This study was financed with the aid of a studentship from Plymouth University.

A record of activity is attached with this thesis detailing the papers which have been published during the course of this study (see page vii).

Word count of main body of thesis: 73,955

Signed .....

Date .....

Chapter 1: Introduction

This chapter presents the motivations behind this project and introduces the research themes of the thesis. Five research questions are outlined, which are referred to frequently throughout the body of the thesis. The methods and technical approaches used in this project are introduced to provide some initial context in addressing the different directions taken throughout the research project. The structure of the thesis is provided at the end of the chapter.

1.1 Motivation

The act of humans making music has always been a physically directed process. Our bodies use energy to disturb the air surrounding us so that changes in air pressure resonate from musical instruments or through our vocal tracts, off materials and surfaces, and finally through the bodies and auditory senses of those listening. The beating of a drum, the bowing of a violin, and the breath channelled through the vocal chords, all create sound as the result of physical exertion, delivering ranges of gestural expression that through context speak to us in emotional and aesthetic languages. When played differently drums and violins can turn music into whole different styles or genres. And the sonic vocabulary of the human voice can seem almost limitless, from the ancient style of Tuval throat singing, to opera singing, or Jazz and Punk styles. But what happens when there is no physical direction? What mechanisms exist for people whose bodies are not physically able to create music via traditional means? And how can music making become accessible to individuals who have no movement abilities whatsoever?

The field of assistive technology is an excellent example of how technology can attempt to replicate physical movement towards improving quality of life, even toward rehabilitation and improvement of physical conditions (Cook 2002). In terms of interfaces for providing music control, little in the way of information on assistive technology for those who have extremely limited or no physical movement exists, such as conditions of paralysis (Magee 2006). This is because in general assistive technology extrapolates whatever gestural movement users are capable of, and amplifies this for control over a specific task or role. For the majority of assistive technology to work *some* physical movement needs to be possible. This leaves a significant gap in the availability of music-making tools and interfaces for users who are unable to perform any, or only extremely limited, physical motor functions.

The brain is often referred to as the final frontier in the understanding of the human physiological make-up. It is responsible for so much beyond the simple control of our physical interactions with the world. It manages the intangible aspects of what makes us human; behaviour, emotion, personality and memory; and yet in comparison to the rest of the human body we understand very little about the brain.

Studies of the brain provide a variety of fascinating approaches for interpreting the behaviour and the mechanisms of how the brain works. To name a few, the area of neurophilosophy questions the relationship between the mind and the brain, and the issue of defining conscious feelings and what make us conscious beings. Neuroaffect is the area of emotional reasoning in the brain, and computational neuroscience is the study of how the brain operates as a computer (Rolls 2012).

Brain-computer interfacing (BCI) seeks to provide users with the means to communicate and interact with their environment, using only their brainwaves. *Electroencephalography* (EEG), the method of detecting brainwaves via electrodes placed on the scalp, is commonly used in BCI applications. Electrical activity that is detected by the electrodes forms the basis of signals from which control is derived. Chapter 2 provides a fuller account of the EEG methods used for BCI. The growing field of BCI offers serious potential for developing channels of communication and interaction, aided by computer systems, with the rest of the world. Music shares these two criteria, communication and interaction, and the ability to create *brain-computer* ***music*** *interfaces* (BCMIs) that can contribute to controlling these elements through brainwaves forms the inspiration behind the body of research presented in this thesis.

The origins of this project trace back to music sessions I attended at Penrose Special School, Bridgwater back in 2010. The sessions were run by Drake Music, a charity who specialise in providing access to music for young people with disabilities, through technology. During these sessions, I observed the technologies that were being used for music making by children with a wide range of physical disabilities.

In addition to the expertise and enthusiasm of the staff, I was struck by the range of interfaces on offer that provided musical interaction, and a subsequent sense of both enjoyment and of feeling part of a group - directly relating to both communication and interaction through music. Switches, buttons and sensors were pushed, hit and activated, alongside more sophisticated interfaces such as the Soundbeam[1] interface, connected to the *Digital Audio Workstation* (DAW). Ableton Live[2]. Two thoughts stayed with me from my time with Drake Music, and were in the forefront of my mind as my research began its initial steps. The first was an awareness that interfaces do not need to be complicated to be musically engaging and enjoyable, in fact the opposite was true with Drake Music as providing accessibility to music provided a simple entry point to music making, for example, *hit this and hear the sound*. Also, if there is a low level of entry, for easy accessibility, then complexity and accomplishment can be developed later. The second thought, and the one that convinced me of exploring the brain as a viable option for music, was that all of the interfaces I observed required a discernable level of body function control. I considered what what the available options were if a user without the ability to physically interact with the devices, which in general required control over hands, feet or limbs. In the sessions, and through some initial research I found no available interfaces or devices for those who had severe motor restrictions or who were unable to move. This helped form the basis of the first two desirable system criteria for developing a new music control interface, control over musical communication and interaction. The decision to investigate the feasibility of using brainwaves as an input to such an interface came

[1] http://www.soundbeam.co.uk/
[2] https://www.ableton.com/

shortly afterwards, through exploring the possibility of BCI as a real-time control interface for music, and so the origins of this project were formed. For my Master's project I worked on a collaborative BCMI with researchers at the University of Essex. For this, I designed the music mappings and built the musical engine. The system was built for trials at the Royal Hospital of Neuro-disability, London UK, where a patient with syndrome, a condition of physical paralysis but full cognitive awareness, had expressed an interest in such a system. Contributing to the project, as I watched the patient play the system with ease and enjoyment, made up my mind to pursue this research further. I was could excited not only to explore the creative possibilities of such technology, but that BCMI could have important implications as recreational and therapeutically tools for the physically impaired. The feedback from the patient helped me focus the direction of my research into BCMI systems to enable user control, where they able to communicate that:

"… it felt great to be in control again"

It was during the early stages of the research that I ruled out undertaking research from a micro-technical point of view, I was more interested in the wider technical aspects of designing and building systems for specific applications of BCMI. A significant body of BCI research is concerned with minutiae of improving particular BCI statistics, and the focus of this thesis is on developing communication and interaction channels through the applications of BCI systems. Traditional BCI research looks to continually improve BCI signal processing (Wilson and Palaniappan 2009), stimuli design (Mehta, Hameed et al. 2010) and machine learning techniques for statistical analysis of brainwaves (AlZoubi, Calvo et al. 2009). This thesis builds on findings in these areas for designing practical, real-time BCMIs towards active or passive control for music communication and interaction.

The topic of researching brainwaves solely for therapeutic or medical improvement through music control was too big to do sufficient justice due to the logistics of conducting medical trials. Because of this, there are two strands to this research. The first, and most

predominant, is the study of BCMI for musical creativity. The second strand, is the implications of these systems for their use in music therapy scenarios, specifically for users with physical disabilities. I wanted to look beyond the efficacy of using brainwaves for music, to the creative possibilities available using BCMI for my own artistic and musical practice, and this has implications for users of all abilities. I wanted to explore the boundaries of control in creative applications of BCMI, for example whether complex forms of control are achievable, and how brainwave control can be communicated to an audience in a music performance setting. These issues do not differ when a user has physical impairments or not, as the nature of BCMI interaction is identical for all users, regardless of physical limitations.

1.2 Research Questions

The objectives of this research project are constructed with regards to the challenges presented in using brainwaves for music control. Towards achieving this in new applications, the following research questions are addressed:

RQ1. How can brainwave measurement provide a suitable platform for real-time control over musical parameters?

Addressing this question requires a study of previous research in the field of BCMI. In the past, BCMI systems have been developed for a range of musical and user-oriented objectives, which in general approximate activity across frequency bands in EEG, and map the voltage power to music parameters, usually with no means of explicit user control. An important objective in this research is real-time music control with brainwaves, and this requires an investigation into BCI techniques that could be applied to music. There are examples of BCMIs where user control is not a primary concern. BCMIs have been proposed for listening to the effects of medical conditions through data sonification, and other BCMIs apply creative mapping rules to construct musical forms from complex and seemingly random EEG data. A study of the literature in chapter 2 analyses prior cases of BCI and BCMI and identifies the technologies, approaches and methods of measuring brainwaves that are suitable for systems that can provide useful, explicit and creative forms of control over music.

RQ2. How can mapping strategies be designed for BCMIs with limited inputs?

Mapping is a key aspect when designing new musical interfaces. Mappings are the relationships between input controls and output commands, and in BCMI for control mappings link user intent to musical parameters.

The BCMI systems developed during this research project contain mapping strategies that explore and exploit the possibilities of control within the limitations of different EEG methods. For example, in chapter 4 the mappings for *Flex* are discussed. *Flex* is a music performance piece for BCMI control. During performances of *Flex* the mappings from four input controls are hidden from the user making control a challenge to attain. As already suggested, basic control devices such as buttons or switches, can provide musical enjoyment, even when mappings are simple. This is because they provide users with a feeling of instantaneous control over, through real-time musical feedback. In a similar way BCMIs do not need complex mappings to be successful, as long as the method of control works. Even so, from a creative line of enquiry exploring the complexity available with a new interface presents an interesting avenue. *Activating Memory* (chapter 5) provides users with the ability to effect one decision (from four options) every 24 seconds. It is the resulting combination of choices by four different users that combine to create musical complexity, a complexity that is derived from an initially simple form of individual control. In contrast, the BCMI for *A Stark Mind* (chapter 7) provides up to an over 18 simultaneous control options, available at any time. This difference illustrates the limited number of control inputs initially available, and how during the evolution of the research control was expanded. When exploring the creative potential of new interfaces for music it is important to understand how far one can go within the limitations of a system, and the BCMI systems demonstrate this keenness to explore the boundaries of control, reflected in the range of mapping designs across the BCMIs.

RQ3. Can BCMIs be improved in use away from laboratory settings such as traditional music performance environments?

Much of the contemporary BCMI literature presents static systems designed for laboratory experimentation, or for demonstrating proof-of-concept pilot systems in controlled and predictable environments. To design BCMI systems that are suitable for use in more traditional music making settings issues such as handling very small electrical signals,

scaling down technologies for portability, unpredictable EEG signal interference, and minimal set-up time need to be taken into account.

Separate aspects of performance aesthetics are also considered as BCMI systems are presented as a medium between performer and an audience. For example, the issue of engaging audiences with technology that requires a performer's motionless interaction presents a difficult restriction to work within (users need to remain still during EEG measurement to avoid interfering electrical signals generated by movement). The communication of musical intent between performer and audience also arises when application of the BCMI is in musical arrangement.

RQ4. Is a multi-brain BCMI feasible for collaborative music making?

Collaboration is a highly regarded feature of music making (Sawyer 2006), providing unique channels of subconscious and implicit communication, interaction and even learning between participants (Barrett 2006). If a BCMI system could successfully provide control over aspects of music for one user then the integration of multiple users affecting control within a BCMI could provide a very useful contribution to the role of providing new channels of communication and interaction between participants in a BCMI for multiple users. This hypothesis is tested in this thesis, through the development of two very different multi-brain BCMI systems, demonstrated in the pieces *Activating Memory* and *The Space Between Us.*

There are two approaches to generating EEG control presented in this thesis. The first, and most dominant in this study, uses active control, where a user can generate explicit control over specific brainwave patterns, and subsequently music. The second approach is passive control, whereby brainwave patterns generated subconsciously provide the input to musical control. A multi-brain BCMI with active control provides users with the means of intentional musical communication, and such as system can provide explicit musical tasks towards collaborative musical goals. This is demonstrated in the presentation of

Activating Memory in chapter 5. Passive control may not rely on such direct intentions but can present an interesting approach to exploring implicit channels of communication. And this becomes especially apparent when subconscious brainwave patterns are associated with states of mind, which can be represented through music, which can influence these states of mind. This approach uses a technique known as neuro-feedback, which is the process of presenting brainwave patterns to the user through music, with the potential for self or even collaborative regulation. When two or more subjects are involved there could be potential to regulate the patterns of each other and enjoy shared, musical experiences. Chapter 6 presents two BCMI systems that approximate emotional indicators, through monitoring physiological affective states, using EEG. This affective channel of communication shows potential for enhancing collaboration in music making in a wider context, for example in the roles of therapist and patient (Rolvsjord 2004).

RQ5. Can brainwave detection methods be combined to improve control in BCMI systems?

BCMI control is bound by the limitations of the particular EEG measuring method being employed. In the field of BCI there are no single active control methods that provide simultaneous control over multiple parameters, in a way that is intrinsic to more traditional music making. Innovatively combining control methods could, in principle, provide this extra dimension in a similar vein to affecting more than one physical control at once when playing a musical instrument. Likewise, in digital music performance control over multiple features is important. For example, a melody in a MIDI score might require both pitch, timing, and velocity information to modestly represent a performance; in a real score, further details might be required to fully represent it; in a performance, even more details might be required to realise the score as audio. Therefore designing complexity in control is useful for musical applications. This project explores the hypothesis of combining brainwave control methods to control a wider range of musical parameters. New mapping strategies are proposed towards managing overlapping brainwave patterns

together with synchronising user control methods, towards providing simultaneous control over multiple musical parameters.

1.3 Methodology

The study of BCI spans the fields of both neuroscience and engineering. As the focus of this research is in applications of BCI, investigations focus on the creative and musical objectives of such a unique interface. In particular, systems are developed with the sole aim of producing new musical performances and designing appropriate mapping strategies. Nevertheless, it is difficult to develop BCMI tools without overcoming technical and engineering issues that are presented, and because of this the research is distinctly multi-disciplinary, taking into account concepts of computer music, computer science, and neuroscience. Commonly, engineering-led BCI research is dedicated to areas that look to improve methods of EEG, such as data classification and noise reduction, and these are important to acknowledge as they can improve the use of BCMI. As well as contributing knowledge to the field of BCI with a comparative study of EEG hardware, a practical incentive of this research was to develop new applications of existing technologies and BCI methods, and adapt them to meet specific musical and artistic requirements. The research aims to improve certain aspects that have a direct correlation to musical applications, and therefore a combination of research methods are undertaken, as each BCMI build on the findings of the previous one. This thesis presents BCMI development through design and configuration of hardware and software systems, developing musical mapping strategies, undertaking user tests, and through musical performances.

Chapters 4-7 in this thesis present a chronological body of work that helps tell a story of BCMI development. The objectives include controlling acoustic instrumentation with BCMI, collaboration and communication using a multi-brain BCMI, and developing hybrid BCMIs that harnesses more than one BCI control method. These arose from gaps identified in BCMI literature, from the study in chapter 2. They are explored through a series of musical compositions and corresponding BCMIs, and resulting performances documented in this thesis demonstrate how BCMI can be successfully applied in traditional music

performance settings. In line with neuro-engineering principles of practical BCI, experiments were conducted to corroborate that the technical designs were not only quantifiably accurate in terms of user control, but that BCMIs were also successful in qualitative terms with respect to user experience.

An important aspect of BCMI that influenced the origins of this research is a lack of commercially available, off-the-shelf BCMI systems. It is not possible to purchase a complete system for the purpose of music control through BCI using EEG. Before designing any musical applications of EEG, a solution to this is required. A number of hardware and software elements make up a BCMI (as discussed further in chapters 2 and 3). These include the EEG measuring hardware, EEG processing tools, classification and feature extraction software, data transformation algorithms for mapping BCI signals to musical commands, a music engine to play sound, and any visual feedback and stimuli tools necessary for a particular BCI method. In fact, there are currently no complete systems available for detecting SSVEP, affective responses or motor imagery (the three methods investigated for BCMI in this thesis) in EEG that directly facilitate music-making. Because of this, a significant portion of the research was spent developing new tools to interface with EEG hardware and achieve this. EEG software that performs EEG detection, classification and feature extraction was developed alongside EEG mapping software and musical engines. Each BCMI presented in this thesis is built around a separate, bespoke musical engine, developed for the specific objectives of the BCMI. Additionally, new hardware SSVEP stimulus units were designed and built, to improve SSVEP control accuracy and provide a standalone user interface. As the project evolved, new software tools were built in response to compositional and performance needs. These ran across a range of software environments and, at times, across multiple computers. This integration of multiple bespoke programs is illustrated in diagrams presented throughout this thesis. A useful tool for other researchers and practitioners would be a dedicated software

application or environment that incorporates the whole suite of individual software elements developed during the project into a single standalone, configurable application.

Throughout the project, software and hardware have been developed using open source tools where possible. This is because open-source software is easy to deploy over multiple machines without license restrictions or the need to purchase multiple licenses and programs can be easily shared and made public - it was important to me that software tools were open-source to encourage others to explore BCMI. This also brings down the cost of entry into BCMI, and promotes openness. The open-source *Pure Data*[3] (Pd) and associated GEM languages (audio and visual programming languages, respectively) were used for designing mapping strategies, building musical engines and visual stimuli and *graphical user interfaces* (GUIs). The SSVEP hardware units are built around open-source Arduino micro-controller boards, and programmed using the Arduino language, which is based on C. A deviation from using open-source platforms was the use of Matlab Simulink[4], a real-time, proprietary prototyping environment, is the only environment officially supported by g.tec [5] EEG hardware, which was available through their sponsorship of the *Interdisciplinary Centre for Computer Music Research* (ICCMR) and this project. The mapping and musical engine tools developed in Pd have been designed to be interoperable with most major open source EEG platforms, aside from Matlab. These include OpenVibe[6], Brainbay[7] and OpenBCI[8]. The first BCMI in this thesis (see chapter 4), uses an Emotiv[9] EEG headset. The Emotiv is a consumer level EEG device aimed primarily at developers wishing to integrate bio-signals with computer gaming. It is affordable, portable, and transmits EEG data wirelessly to a computer, making it an ideal choice for developing a BCMI with these attributes. The Emotiv was used with the open-source

[3] http://puredata.info
[4] http://uk.mathworks.com/products/simulink
[5] http://www.gtec.at
[6] http://openvibe.inria.fr
[7] http://www.shifz.org/brainbay
[8] http://www.openbci.com
[9] http://www.emotiv.com

platform Brainbay for EEG signal processing, another tool useful for creating accessible and hardware-agnostic BCMI tools. When used with the SSVEP technique The Emotiv's performance was comparatively poor and for successive BCMI systems the device was abandoned. For the BCMI presented in chapter 5, more sophisticated EEG hardware was employed. G.tec, a German biomedical engineering company, provided sponsorship for the research, through equipment. The first BCMI developed using this was used for conducting user tests which informed the design of the piece, *Activating Memory*. For this multi-brain BCMI, four g.tec EEG brain caps and associated electrodes and amplifiers were used. This provided more stable and predictable EEG recordings than the Emotiv. The Matlab and Simulink libraries bundled with the g.tec hardware offered the building blocks required to construct processing software for real-time EEG measurement, however further software tools were required to record EEG detection in response to external stimuli, record data during experiments and interact with both visual interfaces (GEM, Arduino, and Resolume were used here) and music engines (Pd, Integra Live were used for developing music engines).

Integra Live[10] is an open source application that provides a graphic user interface (GUI) for Pd to allow for live audio experimentation and performance. Developed by the Integra Lab at Birmingham Conservatoire (UK), Integra Live was used as the music engine for the piece *Flex* (chapter 4) alongside bespoke Pd mapping software to demonstrate how external music software tools can also be harnessed by brain wave control.

To design interoperable software elements that reliably function in real-time, appropriate data transfer protocols are required. This is even more prevalent in multi-user BCMI systems where EEG data from multiple sources needs to be recorded. A series of software tools was designed to pass data both synchronously and asynchronously between software, and to the SSVEP hardware units. There were occasional restrictions that needed to be taken into account, for example Integra Live accepts control data only using

[10] http://www.integralive.org

the MIDI (Musical Instrument Digital Interface) protocol. Data between programs to route processed EEG signals, send mapping rule information and musical control, and send hardware interaction commands were formatted using *Open Sound Control* (OSC). OSC is a data transfer protocol for networking multimedia components and is supported by Pd and GEM extensions. Because OSC is not native to Matlab Simulink a custom function was created to format and transmit EEG data as OSC, using the *User Data Program* (UDP) - a protocol commonly used for IT networking. UDP transfers data via specified ports to an *internet protocol* IP address. Using OSC allowed for the flow of data bi- and multi-directionally between different programs, environments, and hardware, such as to the SSVEP hardware units. OSC data can be sent via UDP between programs on the same computer and across multiple ports if necessary, as well as between multiple computers on the same *local area network* (LAN). This feature was used for synchronising multiple PCs, by sending EEG data, and sending mapping rules for the pieces *Activating Memory* and *The Space Between Us*.

Another software application was used for the piece *A Stark Mind* (chapter 7). Resolume[11] is a video mixing application with built-in effects and advanced transport controls. Resolume was chosen for its ease of use to help the development for the piece focus more on the challenge of synchronising three methods of brainwave control and the acoustic performance of three musicians. Resolume can also respond to OSC control, and piece was configured for transport and effects control via OSC messages sent from mapping rules defined in Pd.

The experimental study documented in chapter 5 used participants from the ICCMR research lab. This was done in accordance with an ethical proposal agreed in the RDC2 research report, submitted prior to this thesis and with ethical approval granted by Plymouth University (evidence is presented in Appendix 2).

[11] https://resolume.com

1.4 Thesis structure

This thesis consists of eight chapters, including this introduction chapter. Each chapter focuses on a specific theme of the project and reports on related research. The remainder of the thesis is structured as follows:

A review of the literature on both BCI and BCMI is provided in **chapter 2**. The chapter consists of three sections.

The first section outlines the technical theory of detecting brainwaves for BCI and BCMI control. This includes an overview of equipment and the range of EEG methods and control techniques that are used in the field.

The second section reviews previous applications of BCMIs. Spanning over 50 years of EEG used for music, the section presents an analysis of the significant milestones in mapping brainwaves to musical parameters. The reviews shows how recent advances in technology, with regards to EEG and computer-music systems, have provided lower points of entry to developing BCMI systems culminating in a higher volume of research over approximately the last fifteen years, paving the way for the BCMIs of this project.

The third section of the chapter outlines the approaches used for BCMI development in this thesis. The section defines system criteria based on the findings and the gaps identified in the literature review. A set of assessment criteria is presented, and this is cross-referenced with the practical implementations of BCMI systems, offering a framework for the development of new BCMI systems.

Chapter 3 presents the technical background that supports this thesis. The chapter outlines the generic systems and methods employed in the BCMIs presented in chapters 4 – 7. Three methods of using EEG data for control are explained, SSVEP, affective state detection and motor imagery, as well as the technical system adopted for BCMI development.

Chapter 4 presents a first iteration BCMI, designed for portability and low cost. The BCMI uses the *steady-state visually evoked potential* (SSVEP) technique for active control. SSVEP is a BCI control method where visual attention to flickering patterns is detected in brainwaves. The chapter addresses the issues that arise from designing a BCMI for portability and live musical control. These include stimuli design, mapping control to electronic music and exploring control through mappings used in *Flex*, a quadraphonic performance piece.

Chapter 5 documents a significant area of development with regards to the improving SSVEP control in a portable BCMI. The first section of this chapter reports on a new custom made SSVEP stimulus unit. An experiment was conducted across 11 participants to determine the accuracy in the SSVEP response generated by the unit across three different EEG measuring devices. A technical report on the design of the new SSVEP stimuli unit is outlined in the second section of the chapter.

The third section of this chapter puts the results of the experiment with the new SSVEP stimulus unit into practice. A new multi-brain BCMI system where control is extended to manipulate the performance of acoustic instruments is presented. *Activating Memory* is a performance piece using four brain caps for users to work together to arrange a live score for four associated musicians.

Chapter 6 reports on research surrounding the use of passive control in BCMI systems. In an attempt to expand control of SSVEP BCMIs, a simultaneous, passive control method was explored. Affective states in EEG are tightly linked to emotional descriptors of a user's state of mind. As such affective responses present an area rich for exploration for control over music that contains strong emotional connotations. This chapter presents a brief overview of music and emotion alongside research in detecting affective states in EEG. A proof of concept pilot study is presented, which forms the basis of determining accuracy in passive control of music. This informed the approach for the affective-BCMI (*a*-BCMI) used for *The Space Between Us*, a performance piece where affective states detected in EEG of a

performer and audience member select musical phrases. Data taken from a performance of this piece is analysed which provides an insight into how affective states monitored during live performance could be affected and manipulated by musical stimuli.

The research presented in **Chapter 7** integrates the method of affective state detection in EEG into two hybrid BCMIs. The first BCMI, *joyBeat,* is a drum machine that simultaneous uses SSVEP and affective states to generate control. The system demonstrates SSVEP mappings to control a step sequencer, and affective responses used to alter the timbral characteristics of the drum sounds.

The second hybrid BCMI in this chapter combines SSVEP, affective response and a third control method, motor imagery. *A Stark Mind* is another performance piece for solo BCMI user for controlling over a dynamic graphic score in real-time. During performance, three musicians perform the music from the score. The score is projected on-stage forming the visual centrepiece of the performance, and demonstrating an novel yet abstract way of communicating BCMI control to an audience.

Chapter 8 concludes this thesis by summarising the conclusions from the earlier chapters. In particular, the chapter emphasises the new contributions to knowledge (see section 8.2.1). The chapter evaluates the how the body of research addresses the research questions (raised in section 1.2), and provides links to the relevant sections of the thesis where this is demonstrated. This chapter also summarises recommendations for future advancements in the field.

Finally, this thesis also includes two appendices, which contain additional information that supports the research. **Appendix** 1 contains audiovisual files relating to the work. The directory of Appendix 1 is structured into folders titled by chapter (Chapter_4, Chapter_5, and so on). Each folder contains the corresponding files referred to in each chapter, such as documentary evidence of performances and audio files of music generated by the BCMI control.

Appendix 2 contains the documentation required for ethical approval from Plymouth University's School of Humanities and Performing Arts ethical committee, including a copy of the participant information pamphlet and the consent form that was signed by participants.

Chapter 2: Principles of brain-computer interfacing: How brainwaves can be harnessed for music control

This chapter is formed of three sections, each with a different focus. The first section, section 2.1, introduces the technical theory behind measuring brainwaves for control.

The second section, which encompasses section 2.2 – 2.9, reviews the background literature that underpins this research, to provide insights into the principles of BCMI, and how the field has progressed to facilitate this project. It focuses on the historical development of BCMI technology through a survey of past literature to analyse the mapping strategies employed and the musical and sonic outcomes. A technical overview of a generic BCMI system is outlined, and the differences found across different implementations of BCMI systems are discussed. These components include EEG measuring techniques, musical and sonic applications, neurofeedback functions and EEG classification methods.

The third section of this chapter, 2.12 – 2.13, presents an outline of the research framework for the BCMIs introduced later on in this thesis. A set of system criteria for BCMI design is outlined, and these contribute to the choices of equipment and methods selected. This set of criteria is also cross-referenced against the research questions from chapter 1. The outcomes of this analysis form the basis of the generic BCMI systems presented in the next chapter.

2.1 Introduction to detecting brainwave patterns

In the early stages of the last century a psychiatrist named Hans Berger invented a method of attaching electrodes to the scalp to record electric fields generated by the neural activity of the brain, a method known as *electroencephalography* (EEG) (Wiedemann 1994). EEG commonly refers to both the method of measurement and the electric fields themselves. These electric fields are extremely faint, with amplitudes in the order of only a few microvolts (Niedermeyer and Lopes da Silva 1987). Not only are the signals faint within the brain, they are further diluted as they pass through muscle tissue, membrane, scalp and hair, before they reach the electrodes. As a result, these signals require significant amplification in order to interface with an electrical or computer based system.

EEG is commonly used in medical practice because anomalies in EEG rhythms can contribute towards clinical diagnosis of neurological conditions such as epilepsy (Misulis K 1997). EEG with electrodes positioned directly on the surface of the brain is possible, and is used during specific surgical procedures. But for non-medical applications, monitoring EEG with electrodes placed on the scalp is best suited to record the surface activity of the brain due to its non-invasive nature. *Functional Magnetic Resonant Imaging* (*f*MRI) is a method used for investigating physiological properties of the brain, specifically changes in cerebral blood flow that are associated with neural activity (Huster, Debener et al. 2012). *f*MRI scanning requires more expensive and bulky equipment than EEG, and although it provides much greater spatial resolution of brain activity as EEG only monitors the activity across the cerebral cortex – the top layer of the brain (EEG is poor at recording activity in lower layers). However, for use outside of clinical studies it is impractical; it is much simpler to measure EEG in terms of equipment costs and space. With regards to the applications of recording brain activity investigated throughout this thesis, a user has more degrees of freedom when paired with an EEG brain cap, as opposed to being physically restricted situated inside an MRI scanner, especially when coupled with other

BCMI equipment. This is also true for positron emission tomography (PET) and magnetoencephalography (MEG), methods that also require expensive, bulky and non-portable equipment. Even though all of these methods require a user to be motionless, with EEG a user can be seated upright with enough immediate space for interacting with other elements of a BCMI system (these are discussed later on). Another alternative to EEG is functional near-infrared spectroscopy (fNIRS), which detects Haemodynamic response (blood oxygenation levels). Like EEG fNIRS also uses a brain cap, but one fitted with optodes instead of electrodes. Promisingly, recent studies have shown how fNIRS can also be used in a BCI control context (Ayaz, Shewokis et al. 2011), including the ability to detect imagined movement for control of external applications, a method known as motor imagery (Sitaram, Zhang et al. 2007). However, the equipment required for fNIRS is currently far more expensive than EEG (Ferrari and Quaresima 2012) and is therefore not as suitable for designing affordable systems. In light of this EEG is a far more suitable platform for measuring brainwaves for interfacing with real-time applications, especially towards developing portable and affordable brainwave interfacing systems.

2.1.2 Measuring EEG

When conducting EEG electrodes are typically placed across the scalp to measure the voltage generated by the brain. Figure 1 shows the 10-10 electrode placement scheme. Electrode positions are labelled as endorsed by the International Federation of Societies for EEG and Clinical Neurophysiology (Society 1994). Electrodes positioned in the locations highlighted in red make up the input channels for the various EEG methods used in the research, discussed in section 3.2.

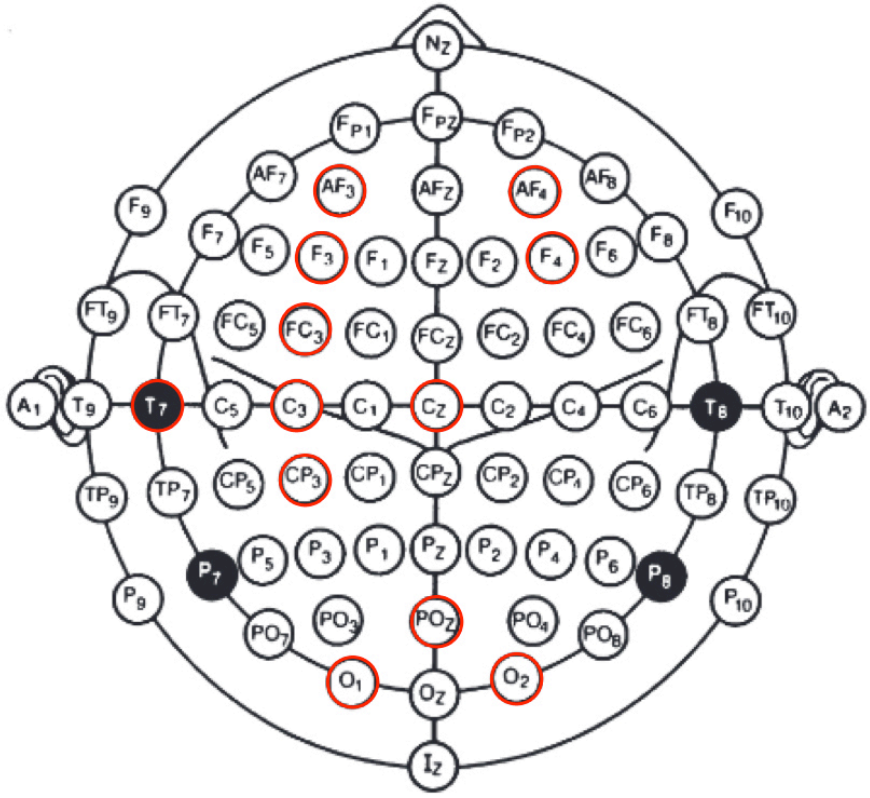

Figure 1. The 10-10 Electrode Placement Scheme. Recommended by the International Federation of Societies for EEG and Clinical Neurophysiology. Image from Herwig, Satrapi et al. 2003.

Electrodes can be used in a variety of combinations, known as montages, which measure EEG alongside a ground and reference electrode. The frequency content of EEG is usually characterised by power spectral densities (PSD) often through applying Fast Fourier Transform (FFT). Other methods of analysing EEG signals include Hjorth, event-related potential (ERP) and correlation (Nidal and Malik 2015).

A monopolar channel consists of EEG measured from one electrode. A bipolar channel, with two electrodes in close proximity, can provide artefact rejection by using a second electrode as a reference for signal comparison. Here, the measure of the sum and difference between the two is taken. In both cases an amplifier measures the voltage difference between the channels and a reference electrode. Using multiple electrode channels allows for a wider range of processing variations. For example, each channel may

be referenced against the average of all channels, or each channel may be weighted against a primary channel, located in an optimal position. A ground electrode is commonly positioned on the forehead to prevent interference from power sources.

With digital technology EEG signals can be processed with ease, and a range of software platforms exist for processing and analysing EEG data.

2.1.3 Common issues when measuring EEG

Recording low voltage electrical signals presents a number of issues, especially when specific patterns are being monitored amidst wider EEG activity. EEG signals can be full of unpredictable elements that can overlap within the specific target regions that are under scrutiny. Interference from conflicting brainwave patterns can also mask the amplified target signal. Furthermore, electrical noise from powered devices such as nearby computer equipment or from static sources, such as user's hair, can also contribute to artefacts in the signal. Correct electrode setup and an optimal measuring environment are crucial to gaining a useful signal, and applying either a conductive paste or solution to electrodes helps to strengthen the contact between electrode and scalp, and increase the *signal-to-noise ratio* (SNR).

The impedance of electrodes provides a measure of the quality of the contact. The higher the impedance of an electrode equates to smaller signal amplitude. An impedance meter is useful for determining optimal impedance, which should be >100 Ω and less than 5K Ω (Teplan 2002).

2.1.4 Interpreting EEG signals

EEG rhythms are classified into four frequency bands that form the basis of most clinical EEG investigations, as shown in Table 1.

Rhythm	*Description*	*Normal*
Delta	< 4Hz	Awake and alert
Theta	4 – 7 Hz	Drowsiness and sleep
Alpha	8 – 13Hz	Posterior dominant rhythm in older children and adults
Beta	> 13Hz	Normal in sleep

Table 1. Description of EEG rhythms including frequency range and related normal state. Activity in other frequency ranges also exists, such as Gamma waves (32 -100Hz) that area associated with memory and perception, or mu waves (8 – 12) which are associated with motor functions, as well as spiking waves across different frequency ranges.

EEG using the full 10-10 scheme is measured across a minimum of eighty-one electrodes, and twenty-one electrode positions when using the sparser 10-20 placement scheme. When detecting specific brainwave patterns over an isolated region fewer electrode channels can be used for localised recordings. For example, alpha waves elicited during relaxation have the highest voltage across the visual cortex (the top layer of the occipital lobe), one of a number of cortices, at electrode positions O_1 and O_2 (Misra and Kailta 2005). As outlined in applications of EEG discussed further on, a useful feature to minimise preparation time is that the number of electrodes can be reduced to focus on localised areas of activity, that are related to specific activities or mental tasks.

2.1.5 Brain-computer interfacing (BCI)

Brain-computer interfacing (BCI) aims to provide applications for communication or for control over systems. Subjects harnessing control over their brainwaves is monitored by computer systems that map control information to communication tasks. With this in mind, BCI is a popular tool in the advancement of assistive technology, especially for users with severe physical disabilities, where control requires restricted or no motor abilities. Wolpaw and Birbaumer (2006) consider BCI to be control provided by a system that can detect the explicit mental commands of a user, which are fed-back to the user in real-time,

acknowledging novel assistive technology applications such as control over wheelchairs and spelling devices. However, the concept of control one's brainwaves is not new, with the first reported discoveries of voluntary alpha wave control by Dr. Joe Kimaya in the 1960's (Kamiya 1962, Kamiya 1968). But it was not until much later, and with digital technologies, that such inventive and useful applications could become a reality.

Methods of controlling brainwave behaviour can be separated into two categories, active and passive control. Active control provides a user with explicit control over brainwave functions, commonly through performing exercises such as attending to external stimuli or mental focusing tasks. This allows a user to exert control over a BCI system's output parameters. A success rate of 70% is commonly used as a benchmark for active control in the field of BCI research (Hammer, Halder et al. 2012), but in practice an error rate of 30% is significant. For applications such as control over music, such error rates can be factored into the mappings, however undesirable. However, for other uses of BCI, such as wheelchair control, 30% error can cause considerable risk. As such, accuracy in active BCI systems is a high priority.

External stimuli for generating active BCI control are commonly either visual or auditory. Visual stimuli is generally better suited to music control as auditory stimuli can distract a user from the resulting music they are attempting to control, unless the stimuli is designed to integrate with the music. Three of the most popular active BCI methods are the *Steady-State Visual Evoked Potential* (SSVEP) response, the P300 response and motor imagery. Passive control plays an important role in systems that detect subconscious EEG patterns for control purposes. Passive EEG is often used as input to musical systems that sonify and musify brainwave signals (see section 2.5), whereas active BCI control can be used as a platform for interfacing explicit brainwave control with musical parameters, thus realising a brain-computer *music* interface (BCMI) (see section 2.9).

The following sections (2.1.6 – 2.1.9) introduce BCI techniques that have been used in previous studies for generating control. These methods are revisited further on this

chapter in relation to musical applications where BCMIs have employed these methods in practice. The methods are then evaluated towards the end of this chapter in relation to their suitability for meeting the aims of this project.

2.1.6 Event-related potentials (ERPs) in EEG from auditory stimuli

Event-related potentials (ERPs) are electrophysiological brain responses produced by perception to stimuli that is presented to a subject. They are time-locked to the event of the stimuli, they have a short duration, and they are sources of controlled and visible variability in brain activity (Donchin, Ritter et al. 1978). ERPs highlight the role of anticipation and perception within brain signals as they can be elicited by deviation from expected events provided by, on the whole repetitive, stimuli (Teplan, 2002).

In 1990 Risto Näätänen reported on a number of experiments in measuring brain activity relating to attention using auditory stimuli. Attention research involving ERPs had been ongoing for over 50 years at the time but Näätänen was keen to distinguish between automatic brain responses to stimuli and responses derived from a listener's attention and their interpretation of the meaning of the stimuli (Näätänen 1990). The idea of a subject being able to shift their attention at will to auditory stimuli opened up the possibility of a BCMI system controlled by a user's attention to specific elements of what they are hearing, with music being an obvious stimulus choice.

Research into attention and sound has long been investigated even before the use of EEG, and earlier research observed a phenomenon known as dichotic listening in regards to how hearing attention is focused. Dichotic listening is the process of paying attention to sound arriving at one ear whilst ignoring sound from the other. When asked to focus on speech arriving at one ear, subjects were often unable to recall speech of the same volume from the opposite ear (Cherry 1953). In Näätänen's experiments he found that the brain reacts to deviations from repetitive sounds automatically, even when the listener focus' their attention away from what they are hearing. This was measured with a P300 EEG

response, where a brainwave spike, also known as a potential, begins with a positive deflection and peaks at around 300ms after the onset of the stimuli. This 'oddball paradigm' implies that when presented with recurring audio information the brain reacts automatically, and predictably, from deviations in patterns.

Throughout the 1990s and early 2000s further research into how the brain responds to auditory stimuli shed light on how the brain processes our perceptions of music. A key area in this field is the study of meaning held within ERPs, building upon previous research into how the brain processes language (Besson and Macar 1987). Here, the term meaning has more depth than mere EEG association to input. (Besson and Fai'ta 1995) demonstrated how different responses within ERPs are elicited when subjects listen to musical phrases that end either congruently or incongruently, in pitch or rhythm. The results also show how differences between musicians and non-musicians indicate that musical expertise can influence aspects of music processing, aside from mere perception.

In 2003 Besson and Schön report that the P600 ERP response (a positive deflection peaking at around 600ms post-stimuli) is associated with syntactic violations in language and music such as grammatical errors and incongruously ending musical phrases. Increases in the N400 (negative deflection around 400ms) ERP were found to be associated with unexpected semantic violations in language, such as *"The pizza is too hot to cry"* (Besson and Schön 2003). The amplitude of the ERP is relative to the degree of the violation; a more abstract meaning results in a potential with higher amplitude.

This research indicates that there is a separate mechanism in the brain for processing music and although the P600 is a slower response that the N400 it nonetheless presents an interesting method for music control due to the correlation with musical congruency. A particular difficulty in using ERPs as a control source in BCMIs is the issue of identifying potentials within other, non-related EEG information. To address this epochs of ERPs are often summed and averaged from many presentations of the same stimuli in order to gauge whether the response is positive or not (Beverina, Palmas et al. 2003). This extra

time adds a significant delay to the signal detection processing, distancing control from real-time musical control, as per the intended applications of my research.

2.1.7 Visual evoked potentials (VEP) in EEG

As already mentioned ERPs within EEG are expected deviances in a signal in response to external stimuli. Because ERPs are time-locked to the event of the stimuli and provide a useful real-time indicator that a user has attended their focus on a specific stimulus. When multiple stimuli are presented this indicator can be converted into a control signal representing a user's choice over the stimuli. ERP response to a single event is problematic to detect in EEG on a single trial basis, as it becomes lost in the general noise of on-going electrical brain activity. P300 and SSVEP are both forms of *Visual Evoked Potential* (VEP) triggered by attending to visual stimuli, and feature prominently in BCI research. In the former, a positive deflection in brain activity, approximately 300ms post-event, provides a method of detecting response to stimuli. In order to determine the validity of P300 detection a number repetitive trials is required to validate a positive detection, and this adds a time delay between user selection and system detection. However, if a user is subjected to repeated visual stimulation at short intervals (at rates approximately between 5Hz – 30Hz), then before the ERP has had a chance to return back to its unexcited state the rapid introduction of the next flashing onset elicits another response. Further successive flashes induce what is known as the steady-state response, a continuously evoked amplification of the brainwave (Regan 1989). This negates a need for performing numerous trials as the repeated visuals are consistently providing the stimuli required for a constant positive potential, translated as a consistent high-amplitude state in the associated EEG frequency, see Figure 2. This response, known as the Steady-State Visual Evoked Potential (SSVEP) can be used as a multiple-choice system, by using a number of icons that flicker at different frequencies. By attending their gaze any of the icons a system could detect which particular icon is currently being used, and apply different control commands to each. This provides a user with explicit choice (a more

detailed evaluation of the SSVEP method is provided in section 3.2.1) over a range of options. A BCI can translate the choice of icon as a separate control command, mapping each input channel to a different function.

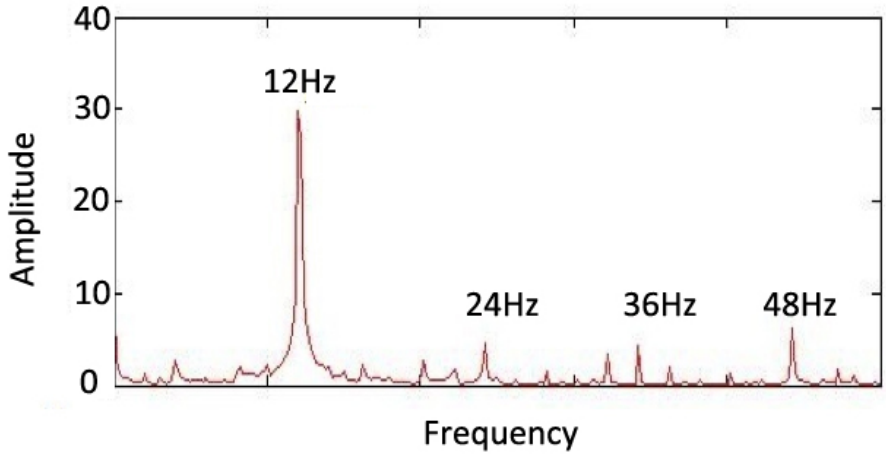

Figure 2. Spectrogram showing a positive SSVEP response detected at 12Hz. Artefacts can be seen in first, second, and third harmonics at 24Hz, 36Hz, and 48Hz.

As well as the selection of commands a second dimension of control is available through the duration of icon gazing. Increasing this elicits an amplitude response in the corresponding brainwave frequency. This allows a user to employ proportional control methods through sustained icon gazing. With SSVEP control two dimensions of control are possible, selection and intensity. This differs from the more common selection only tasks available in other BCI applications. This dual selection and amplitude control was first utilised for control of music in a BCMI I contributed to (Miranda, Magee et al. 2011) (discussed further in section 2.9.2) and this novel method of control is explored for creative purposes to control music later in the thesis.

2.1.8 Motor imagery

Motor imagery is where a user imagines a specific physical movement. The system then monitors any differences occurring in brainwave patterns between imagining this movement and mental relaxation (Pfurtscheller, Brunner et al. 2006).

A number of methods for detecting motor imagery have been proposed in the past. In particular, systems have been designed to detect changes in rhythms that are associated with patterns relating to movement in the motor cortex, located across the top of the scalp. Motor imagery has been successfully detected in mu and beta rhythms (McFarland, Miner et al. 2000) as well as in alpha rhythms (Daly, Williams et al. 2014). In many studies combinations of rhythms are analysed towards providing a more comprehensive study of the effects of motor imagery, such as alpha and low beta rhythms (Neuper, Scherer et al. 2005). A common signal analysis method is the detection of event-related desynchronisation (ERD) of sensorimotor rhythms in EEG whereby a reduction in band power across the brain's motor cortex is indicative of an imagined movement (Pfurtscheller, Brunner et al. 2006). Previous research into motor imagery BCI control has successfully demonstrated up to three dimensions of simultaneous motor imagery detection (McFarland, Sarnacki et al. 2010). Although it is worth noting that the reliability of this study, due to the selection of experimental participants, has been called into question by Allison, Brunner et al. (2012). As motor imagery does not require external stimuli it is highly suitable for use with music control, as it poses less of a distraction than methods that do use stimulus. There are two particular disadvantages of the motor imagery technique in comparison with P300 and SSVEP. Firstly, studies have indicated that it offers a lower level of accuracy than that achievable with eye gazing methods such as P300 and SSVEP (Guger, Edlinger et al. 2011). Secondly, aside from the complex studies of McFarland, Sarnacki et al. (2010) into multi-dimensional motor imagery, the common application of motor imagery is the distinction between two states, and this offers a limited amount of control choices compared to both P300 and SSVEP.

2.1.9 Affective measures in EEG

Further to active control methods, a number of investigations have studied unconscious responses to music that could potentially be used as musical control signals. Arousal and valence are two emotional features, whose origins are examined further in section 6.2.1.

There have been a number of methods reported to measure levels of arousal and valence within EEG, but as yet there is no standardised set of measures (Lamont and Eerola 2011). One common approach to determine positivity within a state of mind is to measure levels of theta and alpha bands across the scalp to determine brain synchronicity, across the left and right hemispheres. Aftanas and Golocheikine purported that this symmetry across the hemispheres of the brain, observed during meditation, is associated with positive emotions and can be used to provide a scale for valence (Aftanas and Golocheikine 2001). In 2001 Schmidt and Trainor proposed a means of categorising emotional responses to music in EEG through measuring levels of arousal and valence in the alpha band (8 – 12 Hz) via electrodes places on the frontal lobe. Here the level of arousal correlates to the spectral power of the band (Schmidt and Trainor 2001). Their experiments indicated that during active listening (attentive focusing or *feeling the music),* music with known emotional qualities can induce predictive EEG patterns. In 2010 Lin et al. monitored levels across four bands, delta, theta, alpha and gamma, across the frontal cortex and parietal lobe to discern relative levels of emotion recorded in response to music listening between self-reported emotions from subjects (Lin, Wang et al. 2010). Here, they observed EEG during music listening and were able to successfully classify four emotional states against user self-report; joy, anger, sadness, and pleasure; obtaining an average classification accuracy of approximately 83% over 26 subjects.

2.1.10 Hybrid BCI

The term hybrid BCI can mean one of two things. One definition is the expansion of a single method of EEG-BCI control to include another bio-signal as another input signal, such as heart rate or galvanic skin response (GSR). The second explanation is the combination of more than one method of brainwave measurement for control (Pfurtscheller, Allison et al. 2010), and it is this definition that is utilised in this research.

To expand user control this thesis proposes combining methods of simultaneous BCI

control in musical applications. Recent research has begun to successfully integrate two different BCI techniques for combined control, but it is common in such studies for a secondary method of control to be used to enforce the main user selections provided by a primary control method. In a report charting the development of their hybrid BCIs Pfurtscheller, Allison et al. (2010) outline the design of a P300/SSVEP hybrid BCMI that uses SSVEP as a secondary control method to strengthen accuracy of user selections through the primary method of P300 selection. Using another, similar approach Pfurtscheller and colleagues implement a hybrid BCI with both SSVEP and motor imagery. Here they use an innovative method of uniting the two methods. To help reduce the interference of false positive values during periods of rest in-between SSVEP selections a motor imagery task is used to turn ON/OFF the SSVEP classification process. This use of a secondary control, acting as a gate either allowing EEG passed through for classification or not, increases the accuracy of the BCI by removing the likelihood of false positives during rest periods.

In another study Panicker, Puthusserypady et al. (2011) also proposed a P300/SSVEP BCMI. In this hybrid system a P300 spelling device can be turned ON/OFF by gazing at the flickering SSVEP frequency of the screen's background.

Two recent surveys by Amiri et. al help establish an understanding of the benefits available with hybrid BCI control, especially in these cases where a secondary control method is used to enforce the accuracy of a primary one. The first of these reviews (Amiri, Rabbi et al. 2013) looks at P300 and SSVEP BCI systems whereas the second's focus is on hybrid BCI systems that use event-related desynchronisation (ERD) alongside SSVEP (Amiri, Fazel-Rezai et al. 2013). Only two methods of BCI are merged in the systems reviewed and in each case a primary method of control is used and like the systems previously mentioned secondary methods of control are used for the same control channel as the primary, to improve the accuracy of the primary method. For example, a hybrid SSVEP/motor imagery BCI was designed for orthosis control (Pfurtscheller, Solis-

Escalante et al. 2010). In this system, SSVEP was used to control stages of orthosis movement, and motor imagery was used to turn the SSVEP LEDs ON and OFF, thus enforcing the SSVEP method by reducing the possibility of false positive values during resting periods.

There are no clear instances of previous studies that combine both passive and active control in a hybrid BCI. This is likely due unpredictability when acquiring passive EEG signals, and because of this passive control is not suitable for control-based systems. However, as examined in chapter 5, in more artistic applications passive control presents itself as a viable tool for creative applications. A survey of BCI methods for computer gaming indicated that users and researchers preferred active BCI methods even though control was often seen as limited due to the number of options available (Ahn, Lee et al. 2014), however this would be an interesting survey to undertake with regards to music-making.

2.2 An introduction to brain-computer music interfacing (BCMI)

The possibility of measuring brainwaves for direct communication and control was first seriously investigated in the early 1970s and the notion of making music with brainwaves is certainly not new. Musicians and composers have been using brainwaves in music for almost the last 50 years. This period reflected a significant trend towards interdisciplinary practices within the arts influenced by experimental and avant-garde artists of the time and a growing engagement with eastern music and philosophies by those in this field (Rosenboom 1972). It is fair to say that biofeedback in music was initially explored by pioneering experimental composers, such as Alvin Lucier, David Rosenboom and Richard Tietelbaum, and the area has been resurrected by a number of notable non-traditional composers and technologists since, such as Eduardo Miranda and Benjamin Knapp. And this is reflected in the wide range of applications and research that has been undertaken over the last decade and a half.

Over the last twenty or so years the world of computer music has been slowly incorporating elements of neuro-technology for interpreting brainwave information in order to develop BCMI systems (Miranda and Brouse 2005). Equipment costs, portability, signal analysis techniques and computing power has rapidly improved over recent times, alongside our understanding of how the brain functions. Now that brainwave detection has become far more accessible the playing field is becoming much larger enabling the two (computer music and neurotechnology) to flourish together. Brainwaves have long been considered to be one of the most challenging of bio-signals to harness, and beginning to understand them through music and sound offers clinical as well as creative rewards; for instance, BCMI systems may benefit Music Therapy where control of music requires very little or no physical movement.

2.3 Mapping and digital musical interfaces

Control has been a key driver in BCMI research as the ability to convey expression and communication through music comes from control. Mapping can be likened to a key that unlocks the creative potentials of BCMI by translating it to control signals that can be understood by a musical system. Put simply, mapping is the connection of input controls (via EEG) to a musical engine. In the pursuit of interactivity in BCMIs, mapping plays a key role in designing creative and practical applications. Alvin Lucier, the first composer to perform using EEG signals, had a desire for more comprehensive mappings within his system to allow for greater musical control (Lucier 1976).

Research into mappings and digital instruments has largely focused on gestural control and physical interaction (Miranda and Wanderley 2006) (Hunt and Wanderley 2003). Goudeseune (2002) presents a comprehensive framework of mapping techniques for digital instrument design, building on the proviso that performers think of mappings as containing the 'feel' of an instrument; how it responds to physical control. Garnett and Goudeseune (1999) refer to the results of mapping as providing *"consistency, continuity, and coherence"* - key factors in the design of musical control systems. For BCMI systems, where either the end user may have limited physical abilities, and when physical movement can cause unwanted noise different strategies for mapping in instruments driven without gestural input, known as *integral interfaces*, is required (Knapp and Cook 2005).

Mappings can be defined based on the number of connections between the input and output parameters. For example, a one-to-one mapping has one input channel mapped to one output channel, a one-to-many mapping has one input channel mapped to multiple output channels, and a many-to-many many mapping has multiple input channels mapped to multiple output channels (Hunt, Wanderley et al. 2000). Although this framework is useful for evaluating system design, it does not take into account the nature of the input

control, or any co-dependencies or rules a mapping may rely on. Goudeseune (2002) recognises the intricacy involved in mapping design, using the term *High-Dimensional Interpolation* (HDI) to define mapping a small number of inputs to a large number of parameters where controls can be interpolated and connected using a variety of rules and techniques.

The investigation of sophisticated mappings in BCMIs, in comparison with other contemporary digital musical instruments and interfaces, has until recently been stifled by the difficulties in eliciting control from EEG information. On the one hand, simple mappings that exemplify EEG control have been popular as they are well suited to this purpose. Simple mappings have been designed to be very effective to facilitate performing and composing with BCMIs for non-musicians (Miranda, Magee et al. 2011). On the other hand new methods of EEG acquisition provide much more accurate and near real-time control than was previously available, and as a result can accommodate far more advanced mapping techniques and compositional approaches. My own performance BCMI piece, *The Warren,* provides a useful example of complex mapping strategies currently available in BCMI development at the beginning of this doctoral project (Eaton and Miranda 2012).

In active BCI control, it is essential to be able to decipher meaning within EEG data that directly correlates with the decisions of a user, be it a mental state or a cognitive task. This quest for meaning in EEG information has long been at the forefront of BCI research, as through precision in interpreting data comes accurate control. Mappings are not necessarily dependant on control, as generative mappings that interpret passive EEG information can produce interesting music (de Campo, Höldrich et al. 2007), but the two can also feed each other in terms of complexity. When control is explicit, the ability to introduce complex mapping strategies for more advanced musical control arises.

Secondar*y* mappings are additional mappings used for music control, and sit below the level of primary mappings and are often unknown to a user. Secondary mappings are

useful for extending creativity in producing music via brainwaves. A secondary mapping may not necessarily be directly presented to a user, but it may be used for time-based data harvesting for algorithmic rule based mapping, or it may simply not take precedence over a primary mapping.

2.4 Approaches to BCMI

BCMI systems can differ in terms of application, cost, equipment type and signal processing, data handling and mappings. However, all are likely to consist of the following common elements, and connected together as shown in figure 3.

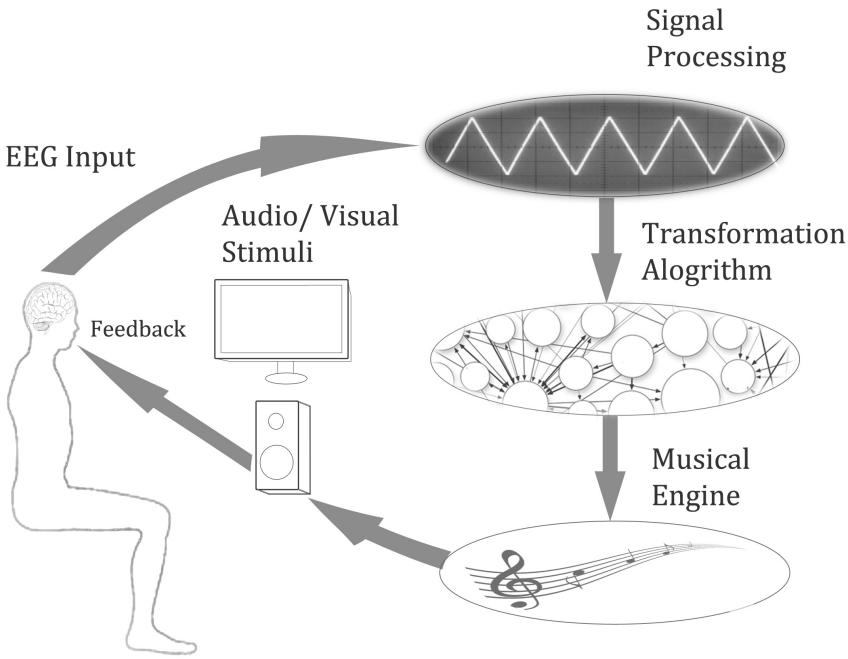

Figure 3. The makeup of a typical BCMI system. EEG is measured using electrodes placed across the scalp of a user. Separate software procedures are required for signal processing of the EEG signal, transforming the data into a control signal and a music engine for translating the control signal into a functional musical controller.

- **Stimulus.** This element is used for BCI methods based on auditory and visual stimuli. This can also be combined with a control feedback visual interface, for BCMIs with visual stimuli.
- **EEG Input**. Electrodes placed on the scalp, positioned with a brain cap.
- **Signal Processing**. Signal Processing. Amplification of electrical activity prior to digitisation, and data extraction to isolate meaningful information. Filtering and data classification are applied depending on the EEG or BCI technique used.
- **Transformation Algorithm**. Mapping the control signal to parameters of a musical engine. This is where mapping of non-musical information to the music al

information. This can take various forms, from early BCMIs that would use a patch cable from an EEG amplifier into an analogue synthesiser, to modern BCMIs where mappings are designed with software tools.

- **Musical Engine**. The musical system receiving commands from the transformation algorithm. This can be an external electronic device, such as a MIDI instrument, but is commonly implemented in a software environment.

Miranda, Sharman et al. (2003) categorise three types of BCI systems, based on how a system interacts with a user, or as they refer to it, the system orientation. They propose that the system orientation of a BCI is user-orientated, computer-orientated or mutually-orientated, and these are useful when considering studying BCI control of music.

In a user-orientated BCI, the computer is programmed to adapt to the user. Miranda and Sherman define this as a relationship where the computer attempts to read the mind of a user to control a device. Such a system learns how to associate specific EEG patterns from a user to commands for control. Building user-orientated BCMIs can be difficult due to understanding meaning within EEG. When requiring interpretation, control can be harnessed in mutually-orientated systems where this problem is addressed by the system and computer adapting to each other.

In a computer-orientated system, the user adapts to the functions of the computer. The computer model stays fixed and the success of the system relies on a user's ability to learn how to perform control over musical events. A performance piece conceived in 2011 by BioMuse Trio, called *Music for Sleeping and Waking Minds*, uses this approach. The responses of performers' brainwaves are mapped to fixed musical parameters. Controlling their states of mind (or sleep in this case) affects control over the music. Attempts to control musical systems with alpha waves have mostly fallen into this category, such as Lucier's *Music for Solo Performer* as the user has learned to control their EEG in certain ways.

A mutually-orientated BCI system combines the functions of both user and computer-orientation whereby the two elements adapt to each other. The use of mental task classification and on-line feedback help a user and computer to adapt to each other. This was the approach used in my piece *The Warren* (Eaton and Miranda 2012). Here, the system requires the user to learn how to generate specific commands, and features mappings that adapt depending on the behaviour of the user.

Most BCMIs are computer-orientated systems. They allow for fixed parameters that respond to specific brain patterns. Mutually-orientated systems promote two useful things. First, more sophisticated algorithms derived from EEG behaviour can be mapped to music - as a system learns a subject's EEG behaviour over time, this information can be used with primary mappings, and through embedding deeper secondary mappings. Second, a system where both user and computer adapt to each other increases the likelihood of obtaining accurate EEG as both elements are effectively calibrated to optimise the system performance.

There are two types of EEG data used in BCMIs, Event Related Potentials (ERPs) and spontaneous EEG. As previously discussed, ERPs are short deviances from predictable brainwave patterns, directly related to an external event – hence the name.

Systems monitoring spontaneous EEG record on-going EEG data, often across multiple frequencies, for patterns or trends that correspond to specific brain activities, or states of mind. This can also be time-locked to external stimuli, for example music that causes a subject to relax which has an affect on frequency band power. Here, windows of corresponding data lasting significantly longer than those used to detect ERPS are monitored for changes.

Research in applying brainwaves to music making has also been developed with other forms of measurement of brain activity. For instance, *f*MRI has been used to record information about brain activity that has then been used offline to aid musical

compositions. But as noted earlier, *f*MRI is impractical for BCMI as it is expensive, it is not portable, and it has poorer time-resolution than EEG, which means it would not be suitable for real-time control.

Along with BCI control types, BCMIs systems fall into the following three categories with regards to how music is generated.

- EEG sonification.
- EEG musification.
- BCI control.

EEG sonification is direct, linear translation of EEG data into sound, and is commonly used in non-musical, medical scenarios. EEG musification is the connecting of EEG information to sonic parameters, however the EEG data is arbitrary and when possible can offer only loose forms of control (Miranda and Brouse 2005). BCI Control is inherent in systems where direct cognitive real-time control of music is achievable. Some systems (Hinterberger and Baier 2004) use more than one of these approaches. In many BCMIs one approach is adopted, but the BCMI could easily be applied to another by switching the input – the method of generating EEG patterns – and adjusting the music mappings to fit. This is clear in both the work of Miranda and Brouse (2005) and Wu, Li et al. (2010).

Further on in this chapter there is a comparison of accuracy levels reported in BCMI systems. A comparison on equal terms is difficult to comfortably determine due to the wide range of technologies, approaches used, and individuals used as test subjects.

The sonification of data is the translation of non-musical information into sound, commonly through direct linear mappings, such as increases and decreases in a data range mapped to pitch. In such an example, this straightforward sonification has a direct one-to-one-mapping, a single data set of values plotted against time with its values mapped to relative changes in pitch. As data values increase, the pitch increases accordingly. As the values decrease, the pitch follows. Sonification allows for information, from sources as

varied as the stock market (Ciardi 2004) or even the weather (Schuett, Winton et al. 2014), to be transformed into audio. Sonification is concerned with the *sound* of the information relative to itself. In this thesis, sonification is regarded as a passive process, where the term passive reflects hearing numerical or graphical data that have not been actively modified to conform to any musical rules or standards (Vogt, de Campo et al. 2007).

Listening to biological signals plays an important role, from the stethoscope to the beeping of the heart rate monitor. Both of these are methods of hearing the body. The visual complexities of EEG make for sonifying its information an additional aid for monitoring activity. As such, mappings for direct data sonification are normally simple in order to provide an intuitive correlation between brain activity and sound in real-time.

Musifying information means mapping data into organised musical forms (Ox 2010). This adds additional stages beyond sonification as musical intelligence is required to encode the data into a musical framework. Data is scaled to fit musical structures, which can either be led by a musical objective or by discernable patterns apparent within EEG. For example, if the EEG delivers five distinguishable patterns, then these can be mapped to five notes within a particular musical scale, or five chords, or any other suitable musical set. Because raw EEG data is not intrinsically musical, intervention is required by an individual, or a computational process, with musical training, EEG data does not have a time signature and does produced with any associated musical style. or form. Therefore, musification is an approach suitable for composers, sound designers, and artists to inject their own styles into translating EEG. For sonification and musification, spontaneous EEG is used as input. An important factor in the history of EEG musification is the introduction of generative musical approaches. As the EEG information itself is either or extremely difficult or impossible to control and is limited in its meaning, musical complexity can be injected with the aid of generative algorithms that can intelligently musify brainwave patterns. To summarise, the differences between sonification and musification are:

- Sonification produces sound mapped directly from raw EEG data, whereas musification requires a structure of musical rules to be applied to the EEG data, by way of a composer or designer
- Sonification of EEG is more common for monitoring EEG behaviour in medical situations, and is less common for artistic applications, although some do exist.

BCMI systems that sonifiy 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 (Wolpaw and Birbaumer 2006).

For BCI control of music, the system allows the user to exert direct, active control over musical parameters, where the results can be heard. A significant obstacle to overcome when designing BCI control systems that adhere to Wolpaw and Birbaumer's definition is that musical thoughts are extremely difficult to detect in brainwave patterns. As with regular BCI, best results lie in either using non-musical mental tasks that can produce discernable brainwave patterns, and map these to music. Or, for higher rates of control, it is possible to use the methods of BCI control with highest accuracy, that use external stimuli to generate control. Here, musical meaning is generated with mappings that associate active BCI stimuli with control over specific musical parameters.

2.5 Observations on Musifying EEG

Musifying brainwave activity can offer interesting mapping opportunities, without being restricted by the amount of control a user can provide. For instance, Miranda and Soucaret (2008) report on a mapping method that produces melodies from the topological behaviour of the EEG across a montage of electrodes on the scalp. The EEG signal of each individual electrode is analysed individually to infer possible trajectories of specific types of EEG information across a montage of 14 electrodes, listed in Table 2.

Electrode Number	Electrode position
1	Fp1
2	Fp2
3	F7
4	F5
5	F4
6	F8
7	T3
8	T4
9	T5
10	P3
11	P4
12	T6
13	O1
14	O2

Table 2. The montage of 14 electrodes used in EEG Melodies by Miranda and Soucaret (2008).

As an example of musifying with this montage, the BCMI tracks the behaviour of the overall EEG amplitude across all of the electrodes. Figure 4 shows a plot of the amplitude of the EEG for each electrode, for approximately 190 seconds. Each plot is divided into 5 windows of approximately 38 seconds each; the size of this window is arbitrary. The average amplitude is calculated for each window and the electrode with the highest value is singled out (shown by the shaded windows in Figure 4).

The example in Figure 5 shows how the power of the EEG has varied across the montage: the area with the highest EEG power moved from electrode 2 (Fp2) to 1 (Fp1), then it moves to electrode 5 (F4) followed by electrode 6 (F8), where it remains for two windows.

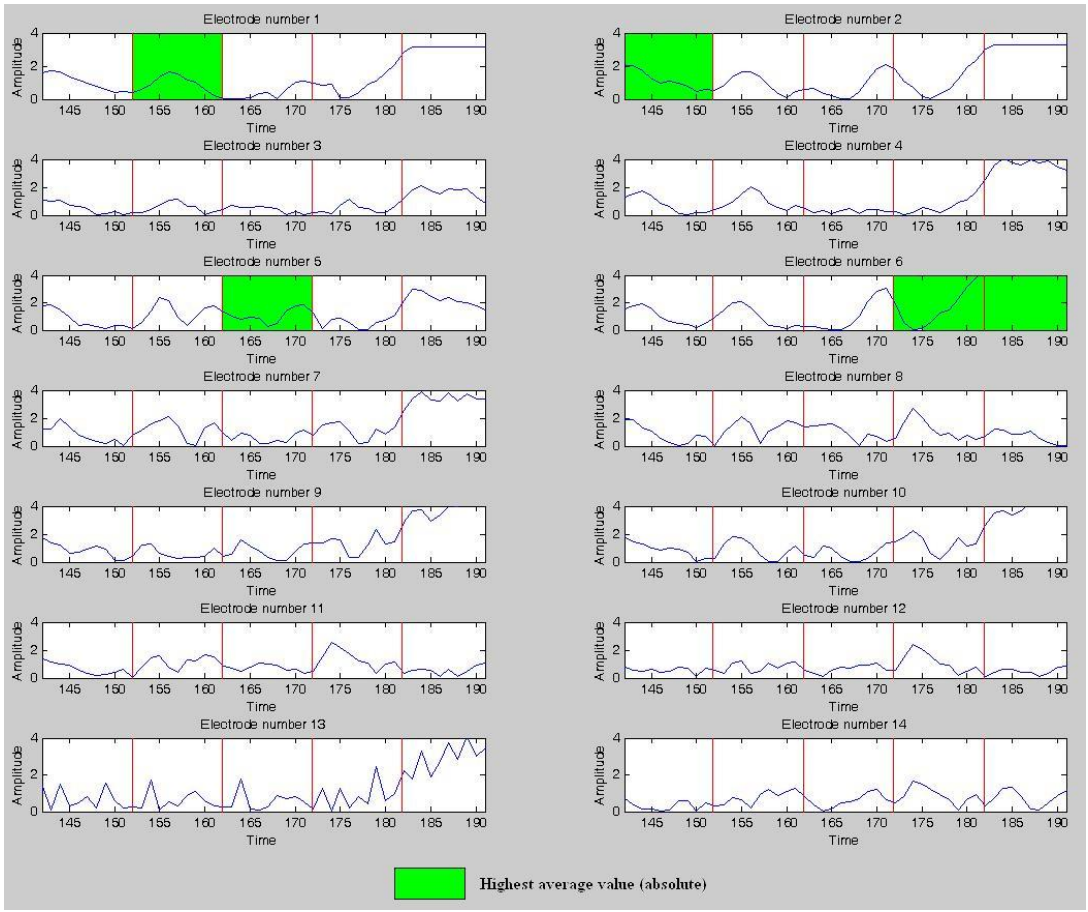

Figure 4. The varying amplitude of the EEG on 14 different electrodes for approximately 190 seconds (Miranda and Soucaret 2008).

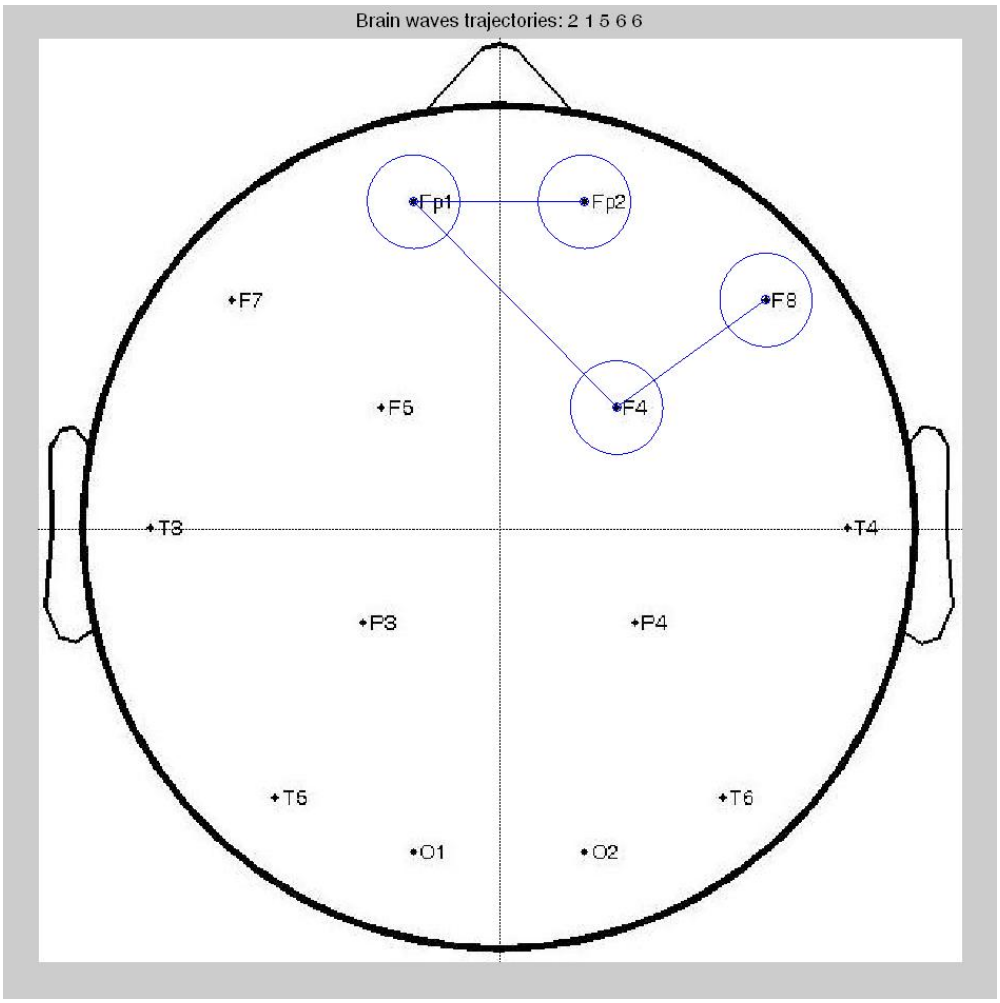

Figure 5. Tracking the behaviour of the amplitude of the EEG signal across a montage of electrodes. In this example, the area with the highest EEG power moved from electrode 2 (Fp2) to 1 (Fp1), then it moved to electrode 5 (F4), followed by electrode 6 (F8), where it remained for two windows (Miranda and Soucaret 2008).

The method to produce melodies works as follows: each electrode is associated with a musical note, as shown in Table 3. The note is played when the respective electrode is the most active with respect to the EEG information in question. Here, the associations between notes and electrodes are arbitrary and can be customised at will.

Electrode Number	Electrode position	Musical Note
1	Fp1	A4
2	Fp2	A4#
3	F7	B4
4	F5	C5
5	F4	C5#
6	F8	D5
7	T3	D5#
8	T4	E5
9	T5	F5
10	P3	F5#
11	P4	G5
12	T6	G5#
13	O1	A6
14	O2	A6#

Table 3. Associations between musical notes and the electrodes of a given montage.

In the case of this example, the trajectory shown in Figure 5 would have generated the melody shown in Figure 6. (Rhythm is allocated by means of a Gaussian distribution function, which is beyond the scope of discussion here.)

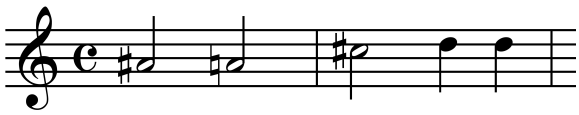

Figure 6. Melody generated from the behaviour of EEG power shown in Figure 4.

Thus it was shown to produce interesting music with the system by forging associations between electrodes and notes, combined with specific generation of rhythmic figures.

A number of analyses can be performed in order to track the behaviour of other types of EEG information. For instance, two concurrent melodies could be generated by tracking the trajectory of Alpha and Beta rhythms simultaneously.

Another example of musification was reported by Wu and colleagues. They harnessed EEG data generated by variations in sleep to compose music (Wu, Li et al. 2009).The pitch and

duration of notes were derived from formulas that mapped each EEG wave to a determinate pitch and its period to duration. Characteristics of the music were explored through experiments with listeners attempting to associate the resultant music with levels of sleep. They developed mapping strategies in their investigations into musical representation of mental states. Figure 7 shows the relationships between EEG features and musical parameters. Here mappings accumulate in order to arrange the content of musical phrases. For example, as time based features of sleep stages differ, compositions derived from Slow Wave Sleep (where activity is high in low frequency delta and theta rhythms), are higher in amplitude and lower in pitch than compositions generated from Rapid Eye Movement EEG (where alpha activity is more prominent, albeit with low amplitudes) (Wu, Li et al. 2010). This ability to directly map time-based features, such as the prominent frequency, gives way for direct musical evocations of the mind's state, allowing a listener to hear, through music, brain states of arousal and relaxation (Figure 7).

The methods used in these examples are able to inform research into more control focused BCMIs, especially where the potential to train EEG through neurofeedback is identified. Where auditory feedback still plays an important role in the field of neurofeedback and medicine (Strehl, Leins et al. 2006), the need for ascertaining meaning within EEG, in parallel with BCMI systems, is just as crucial. Currently, with regards to developing neurofeedback in BCMI systems, there is less requirement for such direct mapping initiatives as used in sonification, and more complex mappings can be introduced. The distinguishing lines between sonification/musification of EEG and BCMI control systems will most likely become further blurred due to the availability of sophisticated musical mappings now available in in both areas. However, although the need for more complex musical mappings within clinical or therapeutic BCMIs are yet to be widely addressed, the potential for more diverse mappings in this field is growing as

mapping features to musical engines becomes easier through data transfer protocols such as MIDI, and OSC.

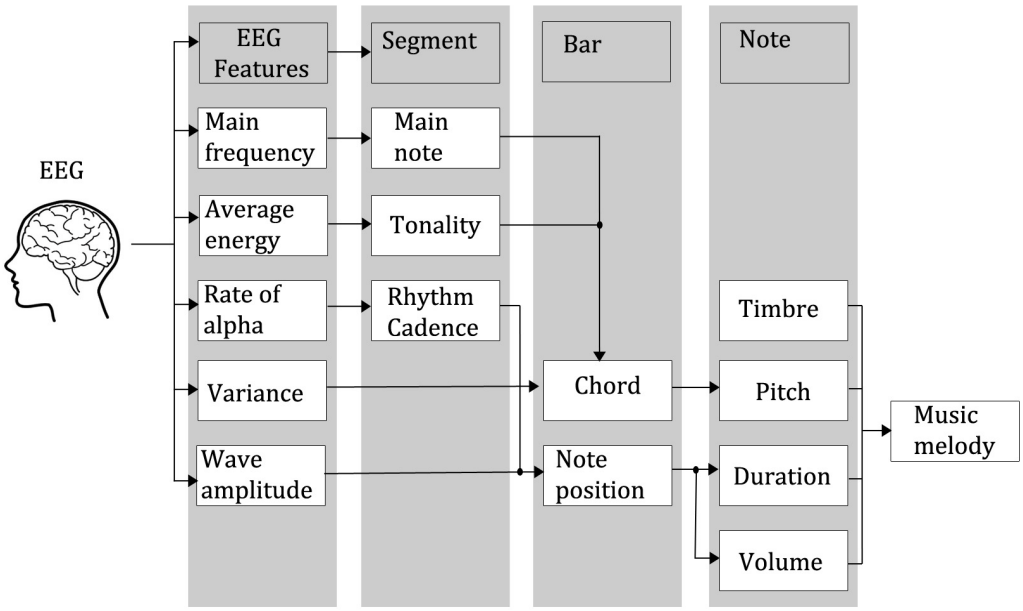

Figure 7. Mapping diagram for musification of EEG proposed by Wu and colleagues. Adapted from Wu, Li et al. (2010).

2.6 Early Research into Biofeedback and Music

In 1965 Alvin Lucier first performed his piece for live percussion and brainwaves titled *Music for Solo Performer.* The piece was inspired by Luciers' investigations, with the physicist Edmond Dewan, into controlling bursts of alpha activity across the frontal cortex using meditative states. Alpha waves, or alpha rhythms, lie within the range of 8Hz and 12Hz, and are commonly associated with relaxed states of attentiveness (Cahn and Polich 2006).

During his performance Lucier amplified his alpha waves, measured from two electrodes positioned across his forehead, using an analogue electronic amplifier and sent the output to a series of loudspeakers. Because the frequencies band of alpha waves lies below the threshold of human hearing, the loudspeakers were coupled with resonant percussive instruments including cymbals, gongs, bass drums and timpani, which rattled away and produced noise as the speakers vibrated, as a novel way of hearing brainwave patterns with musical instruments (Lucier 1976), perhaps part sonification and part musification. When alpha activity increased, so did the resonant activity of the instruments.

This simple method of directly mapping brainwave intensity to instrumentation was the first attempt of its kind to interpret brainwave activity in real-time into a form of music. The theatrical dramaturgy of a man on a darkened stage with wires attached to his head and his brain generating music was surely impressive enough, but Lucier was considerate in his approach by carefully considering the instruments, their relative positions to the loudspeakers, and their layout in the auditorium, to increase and control the sonic outcomes. The input to the system was detection of high alpha rhythms produced in phrases of varying duration, and although limited, this one input input signal was carefully utilised. Either an assistant or Lucier himself manually controlled the flow of alpha amplitude to the system, and mixed the signal across a number of speaker channels. The behaviour of the parameters duration, volume and channel mixing, in response to alpha

activity was used to design the output stages of the system, or the musical engine. These included instrument type, speaker placement, and the involvement of extra resonant or damping materials place on or near the musical instruments, such as cardboard boxes or metal bins. Additionally, a threshold gate was used to allow alpha rhythms above a specifc amplitude level to trigger pre-recorded tape loops of alpha waves that had been transposed up into an audible range that the audience could hear.

In his reflections on the piece, Lucier recognises the importance of how his mapping choices are linked to musical complexity. He even goes as far as to identify an additional mapping strategy he would have liked to have used, but which was unavailable to him at the time. He wished to be able to store time-encoded sections of alpha activity and then map patterns within them to speaker channel mixing. This highlights Lucier as the visionary that he was, seeking to advance the possibilities of what was available to him at the time with ideas that could result in more interesting and complex ways of listening to brainwaves. He would have had to wait many years for technology to be able to realise such an idea, one that would be entirely possible with modern BCMI technologies.

In contrast to Lucier communicating the frequencies of brain activity through resonating acoustic instruments, Richard Teitelbaim, a musician in the electronic ensemble *Musica Elettronica Viva*, began to incorporate bio-signals into his electronic compositions using cutting edge modular synthesisers in the 1970s. Taking inspiration from Lucier and using new advances in analogue synthesisers, Teitelbaum integrated EEG signals alongside other bio-signals into his pieces, many of which, like Lucier's also focused on the use of meditative states of mind. Performed throughout 1967 *Spacecraft* was Tietelbaum's first use of amplified EEG activity as a *control voltage* (CV) signal for a Moog synthesiser. Here, the electrical activities of the brain were electronically sonified by the synthesiser, providing a real-time bio-feedback loop for the performer (Teitelbaum 2006). *Spacecraft* was an improvised piece but it provided the foundation for his later uses of brainwaves that sought to investigate elements of control and musical interaction.

In Tune, one of Tietelbaum's most popular works, was first performed in Rome, 1967. What stands out in later versions of the piece (referred to by the composer as the expanded version of the piece) is the use of a second performer's EEG within his system. Alongside other bio-signals, including heartbeat and amplified breathe, alpha activity was measured and then split into two paths within a modular audio setup comprised of analogue synthesis modules, a mixer and audio effects. Before any audio processing took place, a threshold based noise gate was used to allow only signals that were generated with eyes closed alpha to pass through - the amplitude of alpha rhythms is markedly increased by closing one's eyes. This provided a two-state control switch for performers, system-ON with eyes shut and system-OFF with eyes open. During eyes shut periods, the performer would enter a meditative state to influence the alpha activity further. Precise amplitude control during an ON state of the system's parameters was largely unattainable beyond course levels of amplitude increase and attenuation. With the gate open, the amplified EEG signal was split from an envelope follower into two directions within the system to provide a one-to-many mapping. The first path allowed for a direct DC signal to be mapped to two voltage-controlled oscillators, thus modulating a pre-set centre pitch for each. The intensity of the modulation could be defined and automated by the conductor. The second path sent the EEG signal to an envelope generator, which allowed for variable control of a *voltage-controlled amplifier* (VCA) and *voltage controlled filter* (VCF). This parallel mapping of one EEG signal allowed for real-time modification of pitch, rhythm and amplitude of the synthesised waveforms coupled with magnetic tape recordings being played back through the same VCA and VCF. Again, these mapping choices were not arbitrary but were in keeping with Teitelbaum's artistic aims for the composition. The heavy breathing and sexualised moaning sounds played back from one tape machine being rhythmically enveloped by the alpha was designed to play alongside the live breath and vocal sounds from a throat microphone (Teitelbaum 1976).

This method of signal processing was also used for the second EEG performer, whose alpha controlled a third and fourth oscillator via a second envelope generator, and a secondary tape machine (but no subsequent filter was used in this signal path).

With two performers generating bio-signals Teitelbaum performed the role of conductor. He manually played additional system controls including further synthesis prameters, reverb effect, sound source mixing. Alongside its use of brainwave information as a control input to an electronic musical system, *In Tune* introduces the use of brainwaves as a collaborative musical tool for performers and raises interesting questions regarding the potential influences of bio-feedback between individuals in shared musical environments, signals not just from brainwaves but biological sources.

The fields of bio-feedback and aesthetic experience became increasingly popular in the late 1960s and early 1970s. During his time at the Laboratory of Experimental Aesthetics (part of the Aesthetic Research Center of Canada) David Rosenboom produced a body of works using EEG for music performance pieces, extending explorations into meditative states and bio-feedback. He also conducted a thorough body of research into biofeedback and the arts, definitively recorded in his work *Extended Musical Interface with the Human Nervous System* (Rosenboom 1990).

Other artists at this time were also experimenting with alpha waves, such as the Finnish artist Erkki Kurenniemi's instrument *Dimi-T*, where EEG was used to control the pitch of an oscillator (Ojanen, Suominen et al. 2007). Manfred Eaton's ideas for an adaptive bio-feedback instrument presented in his book *Bio-Music* (Eaton 1971) outlined his concept of a musical brain system powered by visual and auditory stimuli. What is worth noting in his ideas, is that the images or sounds that are presented as stimulus for generating brainwave activity can be semantically removed from the music as long as the corresponding brain activity is one desired by the composer. This concept is now a common tool in contemporary BCMI design, where stimuli are used to generate specific

brainwave information or *meaning*, but are unrelated to the musical outcomes; this is particularly prevalent in contemporary BCMIs that use visual stimuli.

The study of alpha rhythms in music offered a rich era of creative practice. Ultimately, musical and artistic works were restricted by the limits of control that came with generating and analysing alpha. In order to use the brain for more advanced musical applications, new methods of harnessing and interpreting brain information were needed. Yet this early work using alpha waves as input to music systems was an important landmark in the field of BCMI, as it suggested that the notion of music controlled by thought was actually achievable.

In 1995 Pratt and colleagues reported their experiments where children with ADD and ADHD used neurofeedback training with the aid of music with different rhythms, to increase focused behaviour through encouraging the reduction of theta activity (Pratt, Abel et al. 1995). These experiments provided benefits that were still discernable six months later. Years later, sound and music were the focus in Hinterberger and Baier's body of work in providing aural elements to *slow cortical potential* (SCP) driven communicative tools, such as rewarding musical jingles linked to successful EEG control. SCP is a term for amplitude changes across the EEG frequency, usually measured over a period of at least a few seconds. In their system, *Parametric Orchestral Sonification of EEG Rhythms* (POSER) (Hinterberger and Baier 2004), musical mappings are applied to assist real-time analysis of changes in bandwidth frequencies, motivated by research indicating the superiority of audio over visual feedback in a system with multiple inputs (Fitch, Kramer et al. 1994). In initial implementations of *POSER*, features of multiple brainwave rhythms are mapped to MIDI instruments and presented to users. Continuous sounds are modulated in pitch and volume according to changes within the bandwidth of a rhythm. Reports showed that users were able to evoke control over individual EEG rhythms, with up to 85% accuracy during trials, using musical notes as real-time feedback for simultaneous EEG data (Hinterberger and Baier 2004). This approach was later adopted in

a system that screens EEG for dynamic characteristics (Baier, Hermann et al. 2007), such as those prominent in disorders and diseases including epilepsy and Alzheimers (Jeong 2002). Here, events of interest within EEG are mapped to digital synthesis parameters in CSound music software (Boulanger 2000), to aid in the distinction between normal and abnormal rhythms in patients. By connecting expected EEG artefacts to synthesis parameters such as amplitude modulation and harmonic content, a real-time sonic representation of meaningful data is available. In another of their systems (Baier, Hermann et al. 2007), sound localisation via an array of speakers is used to reflect the horizontal location, across the scalp, of the current activity. Further work into these sonification techniques also addresses interaction and user acceptance issues (de Campo, Höldrich et al. 2007).

2.7 Computer Music and the Brain

The music mappings in analogue based BCMI systems were largely defined by the equipment that was used. They were pre-determined by the equipment available, such as Tietelbaum's Moog, they were fixed and they were difficult to change or undo. BioMuse, a hardware and software solution developed by Benjamin Knapp and Hugh Lusted in the 1990s, introduced a major departure from this, with the use of real-time digital processing to process EEG data (Knapp and Lusted 1990).

BioMuse provides a portable kit for digitally processing bio-signals, but what was new in its approach was that it could convert these signals into MIDI data, which at the time was becoming *de facto* for electronic music equipment. MIDI is a standardised protocol for sending music control data between hardware devices such as synthesisers, samplers, and computers. MIDI messages are linked to keyboard controls and include Note-On, Note-Off commands, and velocity and pitch messages. Additional, customisable communication channels exist for mapping input signals to any musical parameter within a device that can receive MIDI data. The range of MIDI signals is 0-127, requiring any input signal to be scaled accordingly (Loy 1985). BioMuse offered a new MIDI control system based on bio-signals, and as well as EEG BioMuse also measured eye movements, muscle movements and sound from a microphone input. The use of the BioMuse and MIDI allowed for an EEG signal to be directly mapped to the input of MIDI enabled equipment, such as a synthesiser, a drum machine or a sequencer. Furthermore, the technology allowed for fine-tuning of input data. An input threshold switch and a channel sensitivity control meant that the system could be calibrated for different users and different applications. Adjusting the threshold allowed for amplitudes over a specified level to trigger a specified MIDI command and increasing the channel sensitivity increased the number of MIDI values in a corresponding range.

The BioMuse software provided the ability to setup mappings using MIDI. With the large number of MIDI commands available, this feature allowed alpha waves to be mapped to note specific MIDI commands (i.e. as Note On or Note Off) or to affect sounds triggered by other bio-signals, such as Control Change messages. From 1987 bursts of alpha activity were sonified via a MIDI synthesiser (Lusted and Knapp 1996), and again the use of opening and closing the eyes was incorporated into compositions to generate significant differences in alpha activity.

Although results of tests had indicated that people could be trained to change mu rhythm amplitude (Wolpaw, McFarland et al. 1991), alpha control was still the most viable option for influencing some control in a BCMI system at the time of BioMuse. But this work brought alpha activity up to date with contemporary musical systems that used digital technologies, and although the method of generating brainwave information was no more advanced, the tools for mapping brain signals to music had improved through the introduction of MIDI.

Music for Sleeping and Waking Minds (Ouzounian, Knapp et al. 2011) is a more recent work using updated versions of these tools. The piece is an eight-hour long composition intended for night-time listening. Four performers wearing EEG sensors affect properties of tones using direct mappings, in order to project basic changes in their brainwave activity to an audience. A spindle is recorded as a spike in activity between 11-16 Hz with a duration ≥ 0.5 secs and combines with muscle twitches during periods before deep sleep (Babadi, McKinney et al. 2012). Alongside alpha activity, delta rhythms and spindles are measured and mapped to parameters of audio. The contrast in input parameters is reflected through the resulting sound. Where alpha rhythms are prominent during modes of light sleep and through closing of the eyes, delta rhythms are associated with deepest levels of sleep. These three classes of brain activity associated with different stages of sleep are mapped to three musical parameters. Within the composition are sixteen tones of differing spectra. Each performer controls parameters relating to four of these tones. An

increase in alpha activity applies a tremolo effect to the tones, prominent delta waves change the timbre of the tones, and spindles trigger enveloped tones through a delay effect with feedback (Ouzounian, Knapp et al. 2011). Whereas delta activity and spindles are not wholly controllable these three elements of brain activity are effectively communicated through the act of watching the performers' sleep as well as listening to the audio.

2.8 Auditory stimuli for BCMI control

By the early 2000s there were several headband-based systems, such as IBVA systems (Miranda 2001), that could play music from EEG data. The majority of these provided two electrodes and limited tools for interpreting raw EEG data. In 2001, Alexander Duncan proposed a hypothetical BCMI system based on musical focusing through performing mental tasks whilst listening to music, alongside EEG pattern classification (Duncan 2001). Duncan (2001) proposed a number of data classification methods for collecting a subject's EEG profile to create an offline neural network classifier, which is used for comparative analysis of EEG readings. The system could effectively be trained to create a model of the user so that in practice changes in the user's EEG could be compared against the model for classifying specific patterns. Here, EEG was extracted through power spectrum analysis, instead of ERPs. Power spectrum analysis uses Fourier transformations to observe the amplitudes of EEG frequencies. In this setup a computer analysed responses within EEG to external stimuli in order to train a neural network over multiple trials. A model is built from the averages of many trials of an individual's response to the stimuli, which is used to train the system. When the system is then engaged in an experiment, it reads an incoming EEG signal and classifies it against the patterns stored in the neural network to in order to predict the nature of the response.

Researchers based at the Interdisciplinary Centre for Computer Music Research, University of Plymouth (ICCMR) implemented this approach in experiments that combined auditory attention with data classification to analyse features within a short epoch of post-stimuli EEG. In 2003 Miranda and colleagues reported on three experiments that investigate methods of producing meaningful EEG, two of which are deemed suitable for practical musical control (Miranda et al. 2003).

In the first experiment, small epochs of EEG measured across 128 electrodes were analysed to detect any differences between the acts of *active listening* (replaying a song in

the *minds ear*) and *passive listening* (listening without focus). Trials were multiplied and looped to build a database of EEG readings which consisted of melodic phrases being played over rhythmic patterns. In different trials during a break between melodies subjects were asked to perform three different tasks. In the first trial to replay the tune in their heads, in a second to try relax their minds without focusing on anything in particular, and in a third to count (internally, not out loud). Trials were carried out in a number of orders for greater disparity and the counting exercise was factored in as a test of whether musical concentration through active and passive listening was extrinsic to standard methods of mental concentration focusing (Miranda, Sharman et al. 2003).

The second experiment set to determine whether EEG could identify whether or not a subject was engaged in *musical focusing* (paying particular attention to an element of music being heard) or *holistic listening* (listening to music without any effort). During the *musical focusing* experiments subjects were asked to focus their auditory attention to an instrument within the music, one that was positioned either in the left or right stereo field.

These tests suggested that it might be possible to accurately measure EEG differentiation between someone engaged in mentally focusing on music and holistic listening. The second test showed that it is possible, although to a lesser degree, to record whether a subject is focusing on sound arriving in the left ear or the right ear, whilst in both experiments the counting exercise provided a different response in the EEG indicating that musical focus uses different brain processing mechanisms that other forms of concentration (Miranda, Sharman et al. 2003).

The experiments were conducted in blocks of multiple trials and the results were derived offline. However their outcomes led to two initial concepts for BCMIs. *b-soloist* is a BCMI system designed to detect both active and passive listening. A continuous rhythm is presented to a subject with regular melodic phrases overlaid. Immediately after the melody is played the system looks for either an EEG reading of active or passive listening. If the reading shows active listening has occurred then the next melody line will be a

variation of the last. If the reading shows passive listening occurred then the next melody played will be exactly the same as the last. *b-conductor* was designed to use musical focusing to affect changes in either left or right channels of music (Figure 8). When presented with music in both channels a user selects a channel through attentively focusing on the instrumentation it contains. At regular intervals the system detects the channel of attention in the EEG and this recognition is mapped to the music, turned up the volume of the focused channel. After a change is made the volume then returns to a default stable position until the next command to change is received.

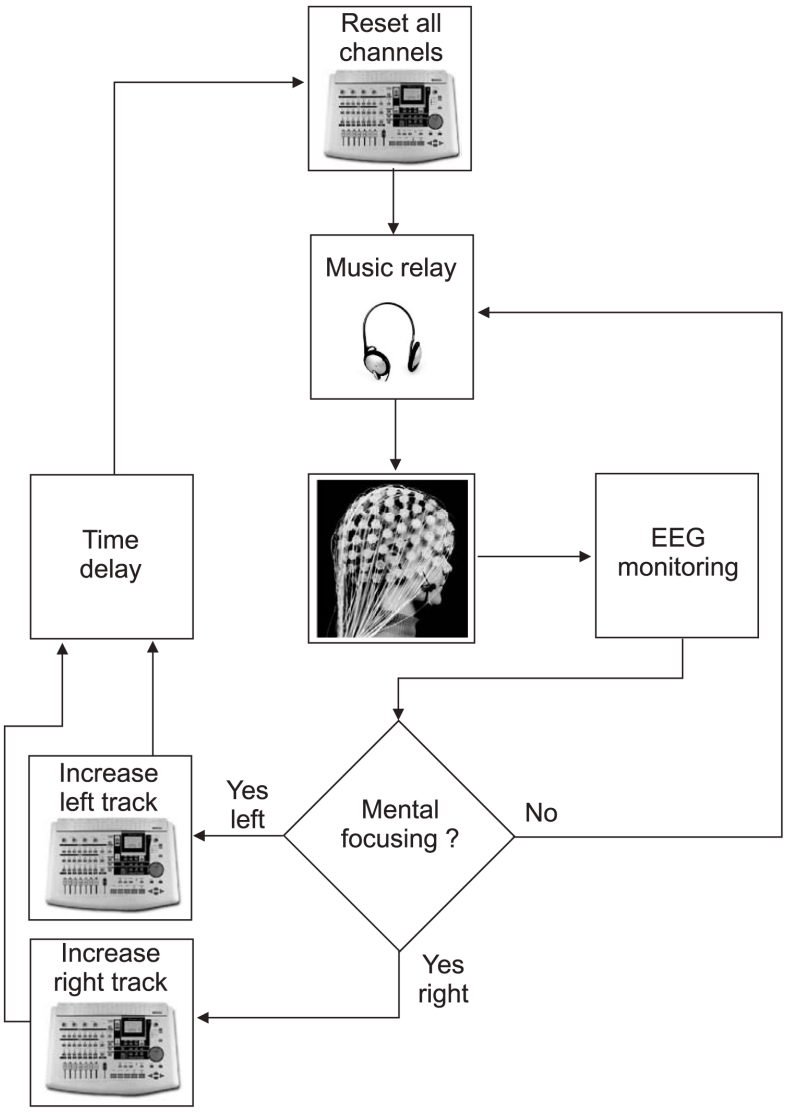

Figure 8. Paradigm for *b-conductor* by Miranda, Sharman et al. (2003).

In 2004 Miranda and Stokes report on a further experiment investigating EEG derived from auditory imagery. Here, they furthered the search for distinctions between mental tasks, looking specifically between *active listening* and other mental tasks based on *motor imagery* and *spatial navigation*, whereby a subject focuses their attention on physical movement whilst remaining still (Miranda and Stokes 2004). Tests again used power spectrum analysis but with three pairs of electrodes (7 in total with a reference electrode) to determine a classification system through building the neural network. Subjects were tasked with imagining opening and closing their right or left hand (motor), and to imagine scanning the rooms of their home (spatial). EEG data corresponding to each task was read by a separate pair of electrodes, calculating the voltage difference between them. It was observed which pair of electrodes produced the largest differences in EEG patterns between each task. Again, results were very positive with the largest distinction recorded between auditory imagery and spatial imagery.

Not only did this later test minimise the number of electrodes for accurately reading overall EEG down to 7, thus likely reducing interference and preparation time, but it also narrowed the gap between BCMIs and EEG techniques within other BCI fields such as assistive technologies, where patients already accustomed to motor imagery might need less training.

Importantly, these experiments indicate that subjective choices are able to elicit predictable brain responses. Unlike the previous experiments with auditory stimuli they do not rely on the subject's expectation or perception of stimuli arriving at a pre-determined time, but allow for a user to impose a subjective decision that has the possibility of becoming separate from the meaning within the music being used as a stimulus. This is a crucial step in the move towards BCI control of music through neuro-feedback.

This idea of subjective control aside, the systems discussed in this section rely on an intrinsic link between the stimuli and resultant music; they are in effect one and the same,

creating a practical neuro-feedback loop. Attempting to implement such a BCMI as an interoperable interface with compositions or musical systems outside brain-related activity becomes extremely difficult when using auditory stimuli as the driver for generating EEG. Issues of attention become prominent when a user is required to focus on specific sounds to generate EEG, which then have a separate effect as they produce or affect unrelated music as the result. BCMIs designed specifically for utilising these features, such as the *b-soloist* and *b-conductor* ideas, rely on the use of the stimuli as the driver and the receiver of neuro-feedback. To design any system where this connection is removed, the element of neuro-feedback can become confused or lost completely, as the cause is disengaged from the effect. To counter this either a compromise in neuro-feedback loss is made, heavy subject training is required to reassign unrelated mappings through decision making, or as suggested by Miranda and collegues higher levels of intelligence is imparted in compositional algorithms detracting from cognitive musical control (Miranda, Sharman et al. 2003).

2.9 Towards visual based BCMI control

Currently there are a number of commercially available platforms offering EEG detection that can be mapped to musical functions; e.g., Mind Peak WaveRider [12], g.tec, Emotiv, to name but three. Mappings are not included, one must design and implement functions that interface the EEG signal protocols used in each system with external music engines. At the time of publication there are few systems that allow for mapping EEG directly to musical programs without direct access to APIs and designing bespoke tools, however the Emotiv system offers the ability to map raw EEG into OSC data, and software such as Brainbay and WaveRider's program provide tools for mapping EEG to MIDI. These systems go no further, and MIDI messages must be received and managed by external software or devices.

In 2005 Miranda and Brouse adopted the approach of designing the musical engine of a BCMI with sufficient artificial intelligence in order to create sophisticated meaning from simpler EEG readings (Miranda and Brouse 2005). Here, they applied a Hjorth analysis, a second method of extracting EEG alongside power spectrum analysis. Hjorth analysis is the extrapolation and measure of time based features within short windows of EEG information. These are referred to as the activity, mobility, and complexity within the reading, measures of which are produced unconsciously as they lie within overall EEG data. Using these techniques the *BCMI-Piano* attempts to guess the mental state of the user and performs real-time generative piano music in response, with features based on the techniques of composers such as Beethoven and Schumann. This is in stark contrast to the previously discussed *b-Soloist* and *b-Conductor*, both of which focus on providing explicit musical control to the user.

In *BCMI-Piano,* again using only 7 electrodes, the amplitudes of four bandwidths were monitored as a reflection of overall EEG activity; delta, beta, alpha and theta. At regular

[12] http://www.futurehealth.org/waveride.htm

intervals in time, and in synchronisation with the playback of pre-composed musical phrases, the system analyses a window of EEG information. In response to the most prominent rhythm detected, the musical engine selects the next musical phrase through the use of mapping rules. As a result the composition is guided by the rules and adapts to the EEG state of the user throughout the piece (Figure 9). This approach may only appear to build on existing systems through the additional use of other rhythms, yet what is new here is the combination of a secondary layer of mappings, that interact with the music alongside the primary mappings of rhythm detection.

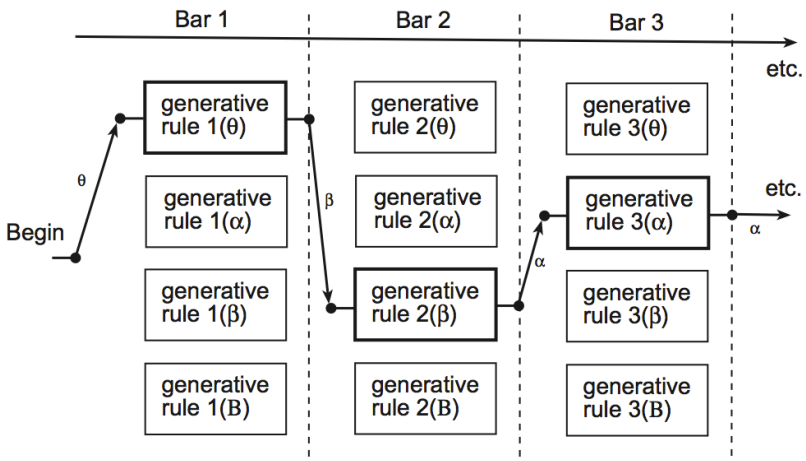

Figure 9. Generative rules to direct real-time composition in the *BCMI Piano* (Miranda and Brouse 2005).

Underneath the direct mappings of rhythms to rules, measures read from the Hjorth analysis are used to modulate musical parameters such as tempo (Figure 10). This adds an element of surprise to the music by injecting some stochastic randomisation into the music generation. This separation of cognitive control and hidden generative rules introduced a new element to BCMI design. As the musician performing with an acoustic instrument responds to spontaneous actions from other musicians, or their own playing nuances, this element of unpredictability provides a novel level of interactivity within real-time music making.

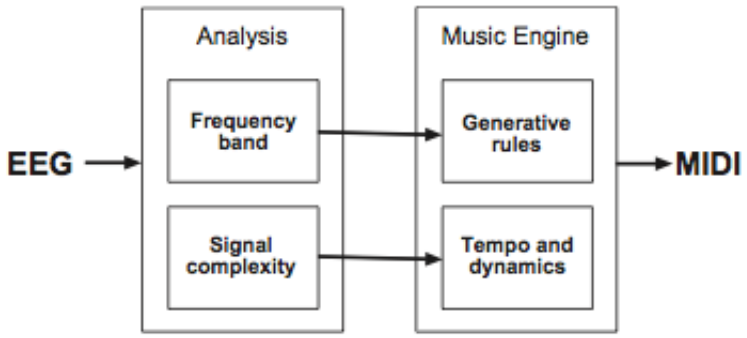

Figure 10. Mapping EEG features to a musical engine in Miranda's *BCMI Piano.* (Miranda and Brouse 2005).

It was at this time that researchers began to highlight a need for methods of cognition recognition and extraction to emanate from the field of neuroscience, in order to fulfil the quota on offer with real-time generative music algorithms. They state:

"Although powerful mathematical tools for analysing the EEG already exist, we still lack a good understanding of their analytical semantics in relation to musical cognition…" (Miranda and Brouse 2005).

Although todays research has brought about many advances this still remains true. Instead of understanding musical semantics in brainwave patterns, BCI methods that use unrelated stimuli to generate control currently offer the most viable means of brainwave control for BCMI.

2.9.1 Visual Evoked Potentials (VEP) for BCMI control

During the 2000's BCI research in assistive technology began to focus on the development of communicative systems that use ERPs derived from visual stimuli, known as Visual Evoked Potentials (VEP).

The P300 oddball paradigm, mentioned earlier with regards to its use in auditory stimuli BCI research, was used by Grierson (2008) for a BCMI controlled by focusing visual attention to stimuli displayed on a computer screen. The P300 potential contains

information relative to visual attention of repetitive stimuli. In the same manner as deviations in auditory stimuli was found to trigger P300 responses (Näätänen 1990) automatically, the P300 could also be elicited by an unexpected interruption within a repetitive visual pattern. In the case of P300 spelling devices, that allow a user to select letters to form words and sentences, the deviant stimulus contains the letter the user desires, and as such is injected with the meaning that a BCI system can knowingly respond to. In the first incarnation of his BCMI Grierson replaces letters for musical notes for a user to select via a visual interface.

Over the course of multiple trials Grierson recorded that four out of five subjects were able to perform subjective decision making, with regards to specific note selection and with no training. These were successfully understood by the system 75% of the time. As ERPs are difficult to detect within EEG, conducting multiple trials improves the reliability of the system to detect these choices and increases the percentage of success. The downside is the time lapse introduced from the initial cognitive decision being made to the end of the trials and the subsequent data processing. Grierson recognises this factor opting for a minimal trial approach in an attempt to link control as close to cognition as possible. The stimuli in this system presented the names of note values over three octaves. Each note name was displayed for approximately 50ms then removed for up to 1800ms, in a quasi-random order. A subject was asked to select a specific note and count each time it was displayed, generating the associated ERP information in synchronisation with each display. Experiments recorded time delays of approximately 12 seconds, with one subject successfully initiating control over approximately 7 seconds with less trials, where total time = flash time x choices x trials; e.g., 50ms x 36 x 7 = 12.7 seconds.

Although these times are lengthy in comparison to EEG response times in other BCMI devices, what Grierson accomplished with this system was the ability to widen user choices to a range of values. Instead of a 'one or the other' decision, the meaning within the stimuli was designed to visually represent many more choices, up to 36 in this case

example. Grierson and colleagues have since developed a suite of BCMI applications based upon the NeuroSky EEG device [13] (Grierson et al. 2011).

This research into ERPs also went as far as to indicate that BCMI control may not need to rely on a subject training their brain to act accordingly to the intelligence of a BCMI, as previously suggested. By relying on the ability of the brain to respond to the focus of attention in a multi-variable environment, no training was necessary as long as the user had the ability to recognise visual events and perform the counting task.

2.9.2 The Steady-State Visual Evoked Potentials (SSVEP) BCMI

The ERP response to a single event is problematic to detect on a single trial basis, as it can be unpredictable to generate and become lost in the noise of ongoing brain activity. However, if a user is subjected to repeated visual stimulation at short intervals (at rates approximately between 5Hz –30Hz), then before the signal has had a chance to return back to its unexcited state the rapid introduction of the next flashing onset elicits another response – again, the SSVEP method. SSVEP was first used in a BCMI system for an individual with locked-in syndrome (Miranda, Magee et al. 2011) as a tool for providing recreational music making. Here four flashing icons were presented on a screen, their flashing frequencies correlating to the frequencies of corresponding brainwaves measured in the visual cortex, located across the rear-centre of the scalp. A user selects an icon simply by gazing at it and the amplitude of the corresponding brainwave frequency increases. Whilst EEG data is monitored online, the system looks for amplitude changes within the four frequencies. The icons represent four choices, always available to the user at the same time. These commands are in turn mapped to commands within a musical engine, as well as being feedback into the display screen to provide visual feedback to the user. The instantaneous speed of the EEG response to the stimuli finally brought real-time explicit control to a BCMI, which required no user or system training beyond the task of

[13] http://www.roll7.co.uk/#!neurosky-games/c3pk

visual focusing. This BCMI system was a collaborative project between University of Plymouth, University of Essex and the Royal Hospital of Neuro-disability (RHN).

As well as the selection of commands, a second dimension of control was available. Through prolonged gazing a relative linear response within the amplitude of the corresponding brainwave could be controlled, (as outlined in section 2.1.7). This allows a user to employ proportional control methods through both selection and amplitude control and, again, differs from previous BCMIs where only selection is available. In this system the research team utilised this control to trigger a series of defined notes within a scale, as illustrated in Figure 11.

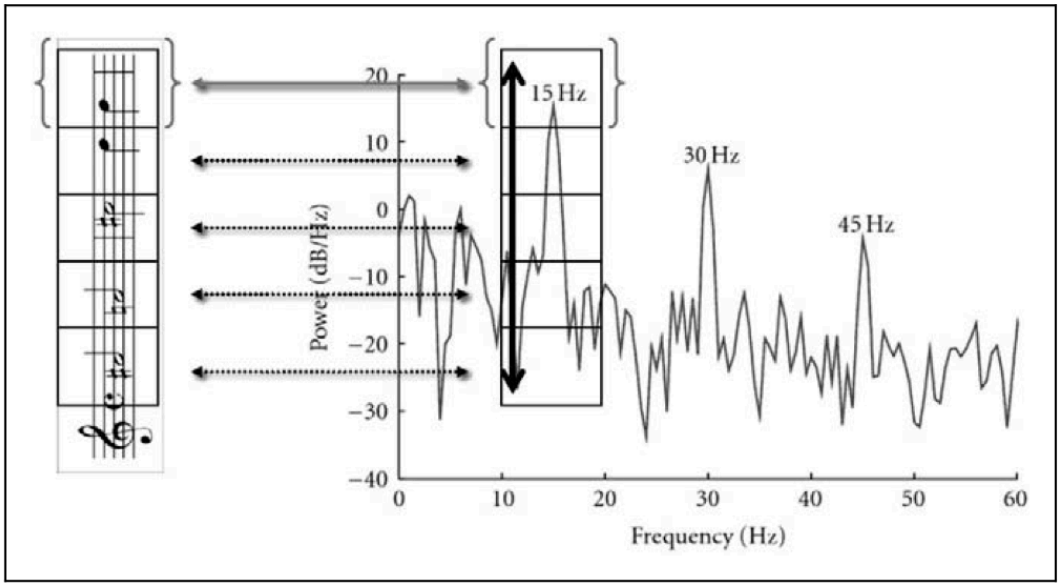

Figure 11. Mapping changes in frequency amplitude to a series of musical pitches. (Miranda et al. 2011).

This SSVEP-based BCMI is the first instance of a system whereby a user can precisely control note specific commands with real-time neurofeedback. It is interesting to refer back to the BCI definition of Wolpaw and Birbaumer (2006) who may well define such systems as outside the realm of true BCI as it relies on the EEG interpretation of eye position, and not mental states. And to highlight again, in the pursuit of real-time control of brainwaves so far SSVEP, in comparison with motor imagery and P300 BCIs, has been found to offer the quickest and most accurate EEG response, and with the least amount of

training (Guger, Edlinger et al. 2011, Combaz, Chatelle et al. 2013). One of the outcomes of this research was the use of BCMIs in collaborative musical applications. In terms of music used as a real-time communicative tool between people, this system allowed for a user to play along with a musician, or potentially, with another BCMI user. This was recognised as an important breakthrough for the potential BCMI systems in therapeutic situations, and for potentially launching the BCMI into a wider field of collaborative musical applications.

In 2011 I adapted this SSVEP BCMI system for a musical composition titled *The Warren*, to help determine whether SSVEP control is an applicable method for electronic music control in a concert setting. *The Warren* is a performance piece designed to explore the boundaries of mapping strategies in a BCMI to generate real-time compositional rules. Control of EEG performs fixed and generative functions that control macro-level musical commands, such as shifts in arrangement, tempo and effects over the master channel, alongside control of micro-level functions, such as control over individual pitches or synthesis parameters. This approach provided a framework for addressing performance considerations often associated with more mainstream digital interfaces. The piece was engineered to communicate expressive musical control, and to provide a loose framework of musical elements for the performer to navigate through, selecting areas for precise manipulation. An important feature of the design was to emulate the unpredictable nature of performing with acoustic instruments, so often safeguarded in electric music performance. Slight deviations of learnt control patterns, or miscalculations when navigating through the piece could result in the *wrong* result, such as bringing the composition to an abrupt end or injecting unwanted silences or dissonance into cacophonies of consonance. This approach forced the concentration of the performer, and underlying the importance of the meaning within the control EEG. To achieve the desired performance complexities and nuances, mapping rules were designed to suit the task (see Figure 12), a break away from previous systems where compositional mappings were intrinsic to the meaning of EEG.

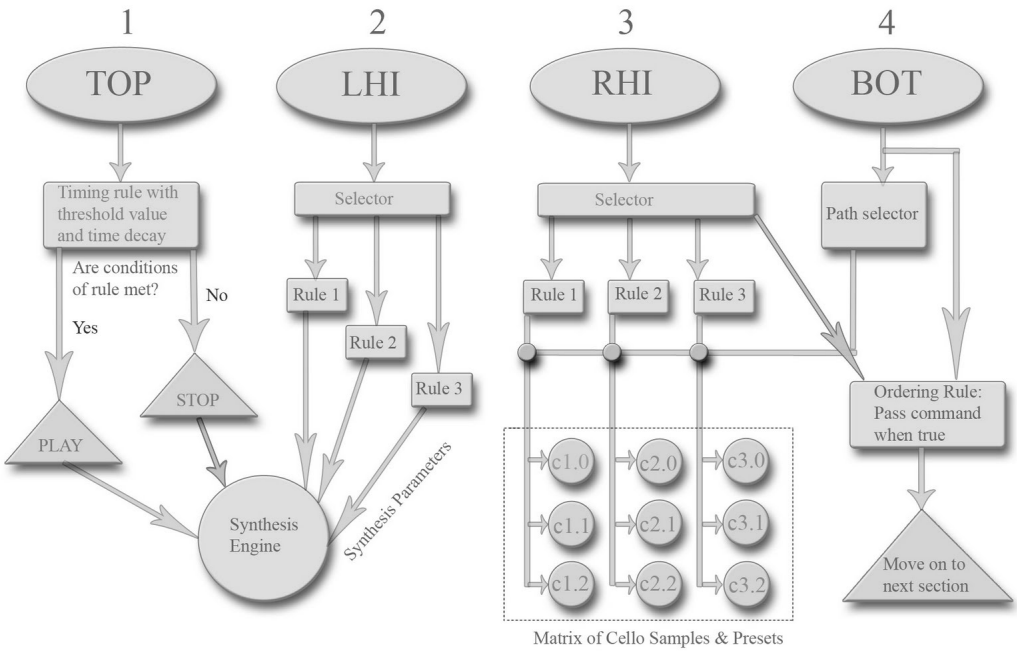

Figure 12. Mapping rules from a section of *The Warren*. Here each icon (labelled 1 - 4) is assigned to a number of rule based commands depending on the requirements of the arrangement.

2.10 Detecting affective measures for BCMI control

In addition to the BCMIs that seek to map mental states to music, such as the levels of tiredness detected in *Music for Sleeping and Waking Minds* (Ouzounian, Knapp et al. 2011), there have been advances towards BCMI systems that map measures of affect, associated with emotions, to music. Two significant pieces of research have arisen in this area, both demonstrating a different artistic approach. *Moodmixer* by Leslie and Mullen (2011) is a BCMI system for an artistic installation setting for two users. In *Moodmixer* two NeuroSky EEG headsets detect variances in mood in each user, in particular the two attributes "*focus*" and "*meditation/relaxation*". *Moodmixer* transforms the correlates of these two measures and plots a co-ordinate for each user onto shared 2-dimensional space. The movement of co-ordinates across the space is then mapped to the volumes of pre-composed music tracks with affective connotations. Essentially the mixed tracks are either turned on or off (fading in and out) relative to the affective values. However, the success of this approach is impossible to determine because the underlying algorithms are unverifiable. The signal processing derivations employed to detect the affective attributes "*focus*" and "*meditation/relaxation*" are closed and proprietary; the manufacturer (NeuroSky) owns them. A worthwhile investigation prior to the implementation of *Moodmixer* would have been to measure the success of the affective detection, perhaps against user self-report. In spite of this limitation, the idea behind the system presents an interesting possibility of a multi-brain BCMI toward creating shared musical experiences in response to the combined brainwave responses of multiple users.

More recently Ramirez and Vamvakousis (2012) proposed a method of detecting levels of arousal and valence within EEG, in response to musical stimulus. In their experiment, they measured levels of arousal and valence over the frontal cortex of the brain across a series of subjects. Stimulus were selected from the IADS (International Affective Digitized Sounds) library (Bradley and Lang 2007) which contains emotion-annotated sounds, and

their results showed that their method was capable of accuracy between 77% – 88%. Their method (expanded in section 3.2.2.1) is both simple to implement and can be used in a real-time BCMI. In their later implementation of the method Giraldo and Ramirez (2013) showcase a BCMI that maps levels of arousal and valence to a MIDI instrument in real-time. This system is able to musify measures of affect and through providing a means neurofeedback reflects a musical representation of affect to a user.

Both of these systems aim to reflect passive, affective measures through simple musical mappings, either selecting one of four tracks in relation of affective levels in *Moodmixer,* or changing parameters of a MIDI instrument. The use of affect as a control signal presents an interesting area for exploration where music can be manipulated in real-time in response to affective measures. There is also potential for applying more complex musical mappings, such as control over multiple instruments and potential for exploring this area in a live performance setting, which has strong emotional connotations and allows for further dimensions of emotional dramaturgy, such as on-stage delivery and the manner of performance. Furthermore, the effects of individual musical preference on the music in such a BCMI are likely to be important and this should be considered in such studies.

2.11 Summary of the literature

BCMI research has come a long way in recent years as meaning in EEG is becoming more understood and easier to detect, as the necessary technologies and computer processing speeds have allowed. However, difficulties in retrieving useful EEG data still remain and pose significant problems for systems intended for use outside of the laboratory. Signal interference from external sources and unpredictable EEG information are issues widely reported in BCMI research. These factors affect the stability and performance of a system, and need to be taken into account when designing and testing a BCMI.

The progress in BCMI research has brought us to a very healthy and pivotal stage. We find ourselves in a climate where constructing a BCMI has become a relatively simple and affordable task. New systems of finite control have provided a strong foundation for integrating BCMIs within wider areas of musical composition and performance, perhaps realised through musical collaborations or interactions with live, external sources, such as dance, acoustic music or other forms of media. Wider research into neurofeedback is also possible through assessing the affects of multiple users of a single BCMI, or multiple BCMIs being played together. Now that the appropriate tools are available we anticipate an increase in research activity across a wider playing field, with a particular emphasis on compositional integration. We are slowly beginning to see brainwave detection creep into everyday use, and as in all successful interdisciplinary areas we expect it to be prominent in clinical, therapeutic and recreational interpretations of what a BCMI is.

It can still be argued that more understanding of meaning within EEG is needed at this stage, not only in BCMI research but in the overall understanding of the brain. As already addressed, meaning leads to control and in turn complexity, and advances in this offer exciting prospects. One area of research that promises to widen the scope of interpreting meaning in EEG is the study of emotional responses in brain activity and evolving research in this field is already uncovering very direct links with emotional responses and music.

(Crowley, Sliney et al. 2010) (Kirke and Miranda 2011). This area is explored in greater detail in chapter 6 of this thesis.

The use of modern BCMI systems for performance in concert settings has marked the arrival of more accessible, responsive and sophisticated platforms for designing and building successful BCMI systems, bringing brainwave control and music full circle. In place of Lucier's percussive instruments are dynamic scores and complex musical engines. Instead of bursts of alpha activity there are layers of sophisticated EEG control on offer. The importance of considering mapping strategies in the development of BCMI systems can be traced all the way back to Alvin Lucier and his *Music for Solo Performer*; an interface that offered such a unique and tangible interaction with brainwaves, from such limited input. With this in mind, and the availability of today's tools, the groundwork has been laid for an imminent rise in creative applications of brainwaves in music coming from composers as well as researchers through approaches applying the complexity in compositional and mapping strategies that have now become a reality.

The Warren demonstrated that BCMI technology could be used in place of more traditional digital musical interfaces as well as in a live performance setting. Furthermore, the SSVEP method presents a useful area for further research as, with regards to explicit control; it improves on previous control methods for a number of reasons. Firstly, a minimal number of electrodes are required compared to other active BCI methods. Secondly, accuracy of the method is easy to determine, either the system detects user choice or it does not. Finally, the second dimension of control on offer is not available in P300 or other active control methods. This continuous amplitude control presents a useful feature that can easily be applied to music in a variety of creative mapping approaches.

There are some limiting factors of the SSVEP method that effect user control. So far SSVEP BCMIs only offer four options, which in terms of musical control can be restricting. Previous SSVEP BCMIs have so far only been used to control electronic music, and it remains to be seen whether control can be expanded in the acoustic domain. Another

factor, which could in fact relate to many of the BCMIs reviewed here, built in the last 20 or so years, is that systems that rely on control via external stimuli are yet to be designed for live performance. The act of SSVEP control in particular is not a particularly engaging sight, as it requires concentration and no movement by a user. The area of passive control in relation to emotion, specifically affect, presents an interesting area for exploration due to the inherent emotional connotations music exhibits. As a secondary method of control, to expand the control on offer with a method of active control, detecting affective response to music seems an ideal candidate. It requires no additional stimulus or user attention, and can therefore be implemented without any additional user effort or distraction from a primary control method. The notion of hybrid BCI control is introduced, and this approach of combining control methods provides a natural step towards expanding control for BCMI.

As with all of the systems presented in this chapter, developing new BCMI systems requires software that is fit for purpose, and this is likely to consist of a number of separate building blocks designed to fit together, each performing a different task. As such, this approach is adopted throughout this project. Finally, modern BCMI systems are physically bulky and heavy, and they are often very expensive. They rely on computers and monitors that are not easy to transport but are necessary due to the required processing power, especially when providing stimuli, processing EEG signals, transforming data to control values and playing back music in real-time. This issue of portability (and associated accessibility) is crucial if BCMIs are to be used in away from the laboratory and in more traditional music making and performance situations.

2.12 Comparison of BCMI system features

Table 4 provides a comparative view of the BCMI systems discussed in this review. Where possible the reported accuracy of systems is recorded in the final column. This relates to a study in chapter 5 where user response against bespoke SSVEP stimuli units used is measured across three different EEG devices. As the unit is designed to provide an improvement in accuracy over the system presented in chapter 4, it is useful to compare this against previous BCMI systems also.

Title, author(s), year	**Control**	**System orientation**	**BCI technique**	**Mapping strategy, input:output channels**	**Musical parameters**	**Musical application**	**Accuracy**
Lucier, *Music for Solo Performer* 1965	Passive	System- (not computer) orientated	Alpha bursts	One-to-one 1: 1	EEG output then split across loud speakers to resonate percussion	Sonification	-
Teitelbaum , *In Tune* 1967	Passive/ Active	System- (not computer) orientated	Alpha bursts (eyes-closed)	One-to-many (signal is split) 1: 3+	CV input to modular synthesiser and effects loop	Sonification	-
Lusted & Knapp, *Bio-muse,* 1990	Passive	User-orientated	Alpha bursts	One-to-many 1: MIDI control	MIDI (non-specific)	Musification	-
Miranda et. al *b-soloist* 2003	Active & Passive	Mutually-orientated	Active listening. Neural network classification system	One-to-one 1: 1	Volume	Music control	Active listening experiments (4). Mean 98% accuracy over 3 subjects

Miranda et. al b-*conductor* 2003	Active	User-orientated	Musical focusing. Neural network classification system	one-to-one 1: 1	Channel volume	Music control	Music focusing experiments (5). Mean 66% accuracy over 3 subjects
Hinterberger & Baier, *POSER* 2004	Passive (but actively controllable)	User-orientated	Band power (no stimuli), SCP	one-to-many 1: 3	MIDI Pitch, volume	Sonification	Various according to measurement. Maximum of 85% regulation recorded by one participant
Miranda, *BCMI-piano* 2005	Passive	User-orientated	FFT band power, Hjorth analysis	Many-to-many 2: 3	Musical style of generative music	Musification	-
Baier, Herman, Stephani 2007	Passive	User-orientated	Measurement of low frequency amplitude changes	Many-to-many 3 *or* 4: 6	Synthesis parameters in CSound incl. Amplitude, duration, modulation etc	Sonification	-

Ouzounain *Music for Sleeping and Waking Minds* 2007	Passive	User-orientated	Alpha and delta wave power, spindle activity	Many-to-many 3: 3	Audio effects including tremolo, delay and 'timbral complexity'	Sonification/ musification	-
Grierson 2008	Active	System-orientated	P300 detection	One-to-many 1: 64	Pitch selection	Music control	"4 out of 5 subjects with 75% or above success rate …"
Miranda, Magee et al. 2011	Active	System-orientated	SSVEP	One-to-many 4: 16	Note-ON triggers, backing music toggle	Music control	-
Eaton *The Warren* 2011	Active	System-orientated	SSVEP	One-to-many 4: 20+ (output mappings change regularly)	Event triggers, effect control, section changes, volume and channel mixing	Music control	-
Leslie and Mullen *Moodmixer* 2011	Passive	User-orientated	Affect – "focus" & "meditation/relaxation"	Two-to-many (per user) 2:4	Mixing music tracks	Music control	Unverifiable

Giraldo and Ramirez 2013	Passive	User-orientated	Affect via arousal and valence detection	Two-to-many	Altering MIDI score data	Music control	-

Table 4. Comparative table of the BCMIs reviewed in this chapter. Previous BCMIs are categorised in relation to their control method, mapping and musical application.

Table 4 offers a comparison of the main features of the BCMI systems that are reviewed in this chapter. With a view to developing new BCMI systems it seems appropriate to identify any areas that arise from studying these previous which present suitable areas for further research. With the aim of addressing the research questions from chapter 1, table 4 highlights four such key areas. As a general observation, the area of active control presents itself as currently the most viable form of providing accurate user control, using external stimuli. The four areas are described as follow:

- Since the bio-interface boom of the 1960s and 1970s, there has been more of a focus towards BCMI systems for research purposes and less towards artistic performance, in particular with regards to active control. With the exception of a few sonification BCMI systems, such as of Bio-muse and *Music for Sleeping and Waking Minds*, there is a significant gap in taking active BCMI systems out of the laboratory and into music performance settings, and as such the musical objectives of active BCMIs have not, without the exception of my work *The Warren*, been geared towards live performance. Over the last decade and a half the groundwork has clearly been laid, in research terms, for putting into practice the principles outlined by BCI studies. The application of active BCI techniques into developing robust and innovative artistic BCMI systems is in its infancy and this is a rich area for exploitation, with regards to both developing new understanding of music control with brainwaves and performing with brainwaves for an audience.
- With recent BCMI research, little focus has been on the application of BCMI for use in music performance settings or in environments conducive to traditional music-making activities. Issue of portability and ease-of-use are key factors when considering developing new BCMI systems for these purposes. New, consumer-targeted EEG measuring devices, such as the Emotiv, may provide a useful area for exploration, as they are lightweight, small, and wireless. As such,

they pose an interesting alternative to bulky medical systems. However, computer processing, required for stimuli presentation, EEG processing and classification, as well as musical generation plays an important role in a BCMI, and the scale of this technology needs to be taken into account.

- There is a lack of research in developing BCMIs for more than one user's EEG. Music participation is often a collaborative process and provides unique and can provide universal channels of communication and interaction. In particular, BCMI systems that provide a novel means of music control for the physically impaired, for example the BCMI presented by Miranda, Magee et al. (2011), present a strong foundation for proposing new systems where multiple BCMI users can engage with one another through music making, which has significant potential for these users and the field of music therapy. The technical challenges of such BCMIs should not be taken lightly, but in principle there should be little reason why the input stages of a working BCMI control system could not be duplicated and its music engine shared for mutual control. From this whole new paradigms of BCMI interaction through distributing control appear on the horizon and pose an exciting area of exploration.
- No previous BCMIs have simultaneously measured an active method of control at the same time as another method of control, in the manner of a *hybrid* BCI. Hinterberger and Baier's *POSER*, Miranda's *BCMI-piano,* and Ouzounain's *Music for Sleeping and Waking Minds* all use more than one method of measuring EEG data simultaneously, but they do not use active control. Combining active control with a secondary control method in a BCMI can take one of two forms. Either, controls are separated, i.e. both control using both methods cannot be generated by a user at the same time, or they can be affected simultaneously. It is the latter of these two that is most exciting in terms of musical applications as control is expanded from a one-to-something mapping to a many-to-something mapping; a

user can affect multiple conditions at once. This act of controlling multiple input channels simultaneously is a common feature in many other digital musical interfaces, with the use of tactile components, such as faders, rotary encoders, buttons and switches, that can be controlled with fingers. This notion is also prevalent in acoustic instruments. For example, when playing the guitar each hand controls separate elements. One hand controls the note selection by pressing the strings on the neck, while the other hand controls how the strings are excited, varying parameters such as the playing style (plucked or strummed), the amplitude, rhythm, and timings. Expanding the methods of control poses a logical step towards broadening the inputs of a BCMI system towards a more comprehensive controller suitable for music control.

2.13 Moving forward: A framework for BCMI design

Following on from the four key areas identified in the previous section a set of system criteria is outlined for the development of the BCMI systems presented in this thesis. Each criterion relates to a specific research question (see section 1.2) and contributes towards specific design decisions that direct the research. Table 5 below highlights the BCMIs that address the system criteria, and the relevant chapters that outline these in finer detail is listed.

The system criteria form an intrinsic part of this thesis, and help identify areas of research that form novel contributions to the field, as summarised in section 8.2.1.

System criteria	Research question	Design decisions	BCMI outcome
Control accuracy	RQ3	Active control offers a more objective approach to measure accuracy. SSVEP has been shown to provide highest accuracy in previous studies compared to motor imagery and P300 (Guger, Edlinger et al. 2011), and P300 (Combaz, Chatelle et al. 2013)	Design of new SSVEP unit (chapter 5) Experiment measuring accuracy SSVEP method (chapter 5)
		Measuring accuracy of passive control presents interesting area to explore	*Affective Jukebox* (chapter 6)
Response time	RQ3	SSVEP has been previously shown to offer fastest response time compared to P300 and motor imagery (Guger, Edlinger et al. 2011)	Design of new SSVEP unit (chapter 5) Experiment measuring accuracy SSVEP method (chapter 5)
Ease of setup/use	RQ3	EEG method. More suitable than *f*MRI, PET, MEG and fNIRS method for real-time signal control	
		Minimal number of electrodes	Adopting SSVEP with 1 electrode channel

Performance aspects – visual engagement & communicating brainwave control	RQ3	This is a consideration for the staging of performances, particularly in the visual domain. BCI control is a motionless practice and additional work is required to create visual stimulation and engagement for viewers	All systems
Feel of the interface	RQ3, RQ4, RQ5	Active control provides a fast response to user choice which is suitable for music control Passive control doesn't offer the same feeling of control as active control but may provide an interesting experience especially when mental states are used to control music	All systems
Communication	RQ1, RQ2, RQ3	Active control provides a direct method of communicating user intent	All BCMIs using SSVEP and motor imagery (chapter 4 – 7)
		Passive control allows for musical communication of subconscious elements, such as mental states and/or affect	All BCMIs using affective state detection (chapter 6 – 7)

Interaction	RQ1, RQ2, RQ4	Expanding the number of control options	SSVEP is expanded to 8 channels in joyBeat & A Stark Mind (chapter 7)
		An environment for multiple BCMI users	*Activating Memory* (chapter 5) *The Space Between Us* (chapter 6)
		An environment for BCMI user to interact with non-BCMI musicians	*Activating Memory* (chapter 5) *A Stark Mind* (chapter 7)
Emotional congruency	RQ3, RQ4	In the pursuit of new music control Ramirez and Vamvakousis (2012) provide a useful method for designing new affective-led BCMIs	Chapter 6
Affordability/accessibility	RQ1, RQ3	EEG. More affordable that *f*MRI, PET, MEG and fNIRS	
		Start by designing a BCMI system using a low cost EEG device and free/open source software. This is revisited when issues of accuracy and reliability arise	*Flex* (chapter 4)

Portability	RQ3	Scaling systems for transportation and ease of use for live performances. Such as: Laptop computers instead of desktops Lightweight amplifiers and EEG hardware	All systems
Multi-brain BCMI control	RQ4	Mapping EEG signals from multiple users to music	*Activating Memory* (chapter 5) *The Space Between Us* (chapter 6)
Multiple dimensions of control	RQ5	Applying simultaneous control methods (adopting a hybrid BCI approach) to musical mappings to create many-to-many mappings. In particular: • SSVEP and affective states • SSVEP, affective states and motor imagery	• *joyBeat* (chapter 7) • *A Stark Mind* (chapter 7)

Table 5: System criteria for new BCMI design in this thesis. With corresponding research questions, design choices and resulting BCMI implementation.

The first two criteria, accuracy and response time are attributes that are intrinsic to musical control (discussed further in section 4.2.1) and as such become a significant focus of investigation. It is important to note that certain criteria, when considered alongside the findings of the literature review, influence the starting point of the research, in particular the use of EEG, the selection of an active control method and issues of affordability and accessibility. Section 2.1 summarises that EEG is currently the most viable method for detecting brainwaves in terms of affordability and size of the equipment. This goes towards meeting the criteria of affordability and accessibility, portability and ease of setup and use. A pro-sumer EEG device is chosen alongside open source software tools with the aim of developing a BCMI system that meets the criteria of affordable/accessible, in an attempt to widen access to the field of BCMI. The SSVEP method is selected for its higher level of accuracy and response time as reported in the literature. These factors are implemented in the *Flex* BCMI, reported in chapter 4. The SSVEP method provides a useful starting place towards addressing the criteria of accuracy, response time, communication and feel of the interface. Further research with the SSVEP method also addresses other criteria such as interaction (as the number of control channels is expanded) and it shows itself to be a suitable method for applying in a multi-brain BCMI. Active control is chosen as a preliminary area for research as it is clearer to validate when success is measured against intent, providing a finite measure of communication. A robust SSVEP BCMI with high accuracy and low response time is achieved with a new SSVEP stimuli unit, reported in chapter 5. The success of these criteria is validated through an experiment in chapter 5 leading to the piece *Activating Memory*. The BCMIs presented in this thesis aim to improve performance through a series of concepts. *Activating Memory,* the BCMI presented in chapter 5 demonstrates how a multi-user BCMI can control the music played by four musicians simultaneously. The piece *The Space Between Us,* a performance piece presented in chapter 6 uses a singer, pianist and live electronics to perform music controlled by another multi-brain BCMI. Finally, *A Stark Mind,* outlined in chapter 7 uses a BCMI system to control an audiovisual performance where a graphical score, controlled by

brainwaves, is projected on-stage, visualising both the brainwave control and the resulting music. Passive control through affective state detection is selected as a possible extension to the SSVEP method. Once an initial SSVEP BCMI has been developed that demonstrates reliability and accuracy, control is expanded with the addition of passive control. Passive control is a suitable candidate for creative use in a BCMI as it requires no extra effort from a user, and as the systems reviewed in section 2.12 illustrate emotional control over music is an interesting area for exploring a new channel of subconscious communication and interaction. The method of detecting affect proposed by Ramirez and Vamvakousis (2012) is corroborated in a real-time passive music selection system and this provides the foundation for the piece *The Space Between Us*, which arranges the score of a live performance based on affective correlates of a performer and audience member. This method of passive control is deemed suitable for combining with SSVEP in a hybrid BCI, and this hypothesis is explored in the piece *joyBeat*, a drum sequencer that maps SSVEP control and affective changes to drum patterns. In the last performance piece presented in the thesis a third control method is added to SSVEP and affective measures in a second hybrid BCMI. After the success of using affective measures and SSVEP together, motor imagery is selected to provide an extra dimension of cognitive control to create further many-to-many mappings. Motor imagery is chosen as a secondary active control method in spite of its relatively poorer accuracy than P300 (Guger, Edlinger et al. 2011), and its limited control options, two in this instance, as it requires no additional stimuli that may distract from SSVEP control, and the manner of generating the required mental states is complementary to both SSVEP and the passive nature of affective measures. This section of the research goes towards meeting the criteria of multiple dimensions of control in a BCMI.

2.14 Summary

In order to understand the applications of brainwave detection and BCMI technologies the history of the field, as presented in this chapter, requires acknowledgement. This chapter has presented the EEG method, classifying patterns and meaning within brainwaves, mapping strategies, musical and sonic outcomes and the different objectives of previous BCMI systems. The analysis of these factors indicates the different ways in which brainwave measurement provides a suitable platform for control over musical parameters, as proposed in RQ1).

The literature reviewed in this chapter has helped identify key system criteria for BCMI development. These are proposed in table 5 alongside related research questions, and how they influence BCMI design. This helps to construct the starting point of the research - the use of EEG, active BCI control through SSVEP, and using portable, affordable and accessible tools – beginning in chapter 4, with the first BCMI system, *Flex.*

The next chapter provides a technical background to the research, outlining the generic EEG methods employed in the BCMIs presented in chapters 4 – 7.

Chapter 3: Technical background

This chapter provides the technical background behind the BCMIs developed throughout this project. An overview of the three methods of brainwave stimulation and detection used in the thesis are introduced; steady-state visual evoked potentials (SSVEP), motor imagery and affective states.

3.1 Electroencephalographic equipment

EEG signals are amplified and then digitised using hardware devices before the signals can be processed in software. Some modern digitisers provide wireless transfer of EEG signals to a host PC and this allows interfacing with a wider range of PCs making technical issues of interconnectivity between amplifiers and computers less of a concern.

Three EEG platforms are used for the BCMIs in this thesis, and are referred to as platforms 1, 2, and 3 from hereon. The first two platforms are produced by the bio-medical engineering company g.tec, who market their equipment for bio-medical research. G.tec's g.Gamma brain cap can fit up to 74 electrodes for the 10-10 and extended 10-20 schemes with a further 86 additional positions, allowing for highly-localised custom montages. The third platform is the Emotiv device, a 'pro-sumer' (professional-consumer) EEG headset aimed the computer gaming market and communicates EEG signals wirelessly via Bluetooth. 14 fixed electrode channels makes the Emotiv in the top range of pro-sumer EEG headset in terms of the amount of electrodes available for EEG.

- **Platform 1.** g.tec g.Sahara active (dry) electrodes and brain cap. Electrodes connect to a g.tec Sahara amplifier, which is in turn connected to a g.tec MOBIlab+ digitiser. The digitised EEG data is sent via a USB Bluetooth adaptor to the host PC.

- **Platform 2.** g.tec g.Gamma passive (wet) electrodes and brain cap. Electrodes connect to a g.tec gamma amplifier, which is in turn connected to a g.tec MOBIlab+ digitiser. The digitised EEG data is sent via a USB Bluetooth adaptor to the host PC.

- **Platform 3**. Emotiv epoc EEG wireless headset. EEG data is transmitted wirelessly via a Bluetooth Adaptor to the host PC.

3.2 BCI and EEG methods used in this thesis

The BCMIs presented in this thesis use a combination of the following three control methods:

- SSVEP control
- Affective responses to music,
- Motor imagery through *event-related desynchronisation* (ERD).

An overview of the three methods is provided in the following sub-sections, with particular emphasis on the features of SSVEP control, which is the primary method investigated in this research.

3.2.1 SSVEP control

This section looks at translating SSVEP responses in EEG and the attributes required in successful SSVEP stimuli. Further insight into the practicalities of optimising BCMIs for SSVEP accuracy is discussed later in section 4.2. An experiment measuring two key factors, SSVEP accuracy and response time, is outlined in section 5.1 alongside a summary of previous research into these two factors.

3.2.1.1 SSVEP Method

The main benefits of the SSVEP method are that brainwave responses to flickering stimuli occur almost instantaneously, and the method requires no training for a user to generate a positive response that can be used for control. Systems can be both calibrated and employ advanced signal processing techniques to adjust to individual user responses for more accurately predicting SSVEP detection and the elimination of noise. However, for an SSVEP-based BCMI to have real-time music control, or as close to real-time as possible, EEG processing must occur on-line. This means that classification of EEG patterns to detect SSVEP must be computed by processing the input stream of raw EEG data whilst a

user performs icon gazing. Frequency spectrum analysis of EEG signals is typically used in SSVEP detection, in particular using the fast Fourier Transform (Wilson and Palaniappan 2011). FFT windows of a larger size can provide greater accuracy in spectral resolution, and therefore greater accuracy in determining positive SSVEP. But a larger window comes at a cost of an increased time delay; from a user's gaze to the system's recognition of the event.

Machine learning algorithms are common for improving the accuracy of BCI control by training the algorithm to better estimate specific EEG responses (Müller, Tangermann et al. 2008, Vidaurre, Sannelli et al. 2011). However, these methods are only valid when a classifier is appropriately trained, and this requires significant time to train the classifier prior to use, unlike more classic BCI that relies on the adaptability of the brain to respond to real-time feedback (Müller, Krauledat et al. 2004). In the past machine learning algorithms that are able to provide high accuracy in classifying SSVEP response are calculated off-line (Liu, Jiang et al. 2012), after the gazing session, but this is unsuitable for a system that intends to use SSVEP detection for real-time control. Furthermore the higher the accuracy of the classifier, then the longer the training session needs to be in order to generate the data with which to train the classifier. As conditions such as time of day, mood or stress levels, environment and localised noise can contribute to a different EGG response in any given individual, spending time training a classifier before undertaking a music making session can be time-consuming and inconvenient. The approach taken in this thesis is focused on developing BCMI systems that work on-the-fly for music making. Thankfully, the SSVEP method does not require significant training, especially in comparison to other BCI control methods. Positive SSVEP response can be detected and harnessed without the need for complex classification systems, and with little user training. For the SSVEP systems in this thesis a classification technique is used that matches a user's response at a given time, and this takes a relatively short time to train; less than 2 minutes to train the classifier across four SSVEP channels. A linear algorithm is

used to recognise whether an SSVEP signal exceeds a minimum threshold value a^{min} that is determined during the calibration phase. Upon exceeding a^{min} a function sends a command to the musical engine based on the user's gaze resulting in the threshold being breached. Aside from this minimum threshold value a maximum threshold value a^{max} represents the highest peak of the amplitude range attainable through SSVEP. Between these two threshold values lies a control range, represented as an amplitude range between a^{min} and a^{max}. This range differs between SSVEP frequencies and individual users. To remove the need for calibration prior to every session the classifier stores a user's a^{min} and a^{max} values for recall for future sessions.

SSVEP is detected with all three different EEG hardware platforms throughout the thesis. For the *Flex* BCMI (chapter 4) EEG signals from platform 3, the Emotiv headset, were measured across the occipital region at electrode positions O_1 and O_2 (see Figure 1). The average measure of these two electrodes is taken as the input channel and processed in the BrainBay platform. Prior to processing, Brainbay is configured to detect incoming data between -100μV to 100μV. The Emotiv device has a DC offset of about 4200mV. In order to reject this offset a high-pass filter is required. This is realised using a 4th order Butterworth filter with a cut-off frequency at 0.16Hz. The signal then passes through four 8th order bandpass Butterworth filters, each with a centre frequency of 6Hz, 7.5Hz, 8.57Hz and 10Hz (corresponding to the four flickering stimuli) and a bandwidth of 0.3Hz. The outputs from the filters are then processed using an FFT function with a Hanning window for epochs of 128 samples to provide approximately ten transformations per second (with a sampling rate of 256Hz).

In the SSVEP BCMIs, from chapter 5 onwards, Matlab was used for real-time processing using a PSD extraction method. This was chosen because for its greater computational efficiency over using the FFT method on laptop computers. In practice this exerted less strain on the PC processor and provided greater stability, especially as processing overhead was needed for music mapping and generation applications. SSVEP control using

platforms 1 and 2 (the two g.tec platforms) uses a single electrode channel placed at position PO_z, with a reference electrode at position C_z on the top of the scalp and ground electrode at position AF_z, on the centre of the forehead (see Figure 1). All three platforms transmit raw EEG data wirelessly via Bluetooth to a host laptop PC for processing. Each electrode channel has a lower cut-off frequency of 0.5 Hz and an upper cut-off frequency of 100 Hz. The sensitivity for g.tec electrode channels is ± 500 μV.

Data is pre-processed in Matlab with a low pass filter to remove DC offset and a notch filter to reduce mains interference at 50Hz. The signal is processed using four or eight parallel band power extractors, depending on whether one (four LED flash frequencies) or two (eight LED flash frequencies) external SSVEP stimuli units are used. Band power in each SSVEP channel is estimated by first applying a Butterworth band-pass filter, order 5, across each target frequency with a bandwidth of 0.2Hz and an edge of -3db for both low and high cut-off frequencies. Then, each sample is squared and averaged over consecutive, sliding windows of 64 samples.

3.2.1.2 SSVEP stimulus frequencies

The actual brain mechanics behind the SSVEP phenomena remain somewhat unclear but it is firmly understood that an oscillating visual stimulus is needed for eliciting SSVEP response in brainwaves (Wu, Lai et al. 2008). The stimulus is commonly in the form of a flickering light (or variations of this theme as discussed in section 3.2.1.5), where a flashing icon with a fundamental frequency f_0 elicits a positive response in the amplitude of the corresponding brainwave frequency, measured across the visual cortex. Positive amplitude responses are also generated in harmonic frequencies, frequencies that are multipliers of the fundamental. Monitoring both the fundamental and harmonic frequencies can be useful for confirming positive SSVEP response, but this approach was not used in the systems developed for this project, due to the computer processing overhead required. In essence, a flickering light can trigger positive brainwave SSVEP

responses in both the fundamental stimulation frequency and lesser so in its early harmonics (Volosyak, Cecotti et al. 2009). SSVEP is detectable across a wide bandwidth, with some studies suggesting as wide as 1 – 100Hz (Herrmann 2001), but in practice stimulation frequencies commonly fall below 20Hz in the approximate range of 6 – 15Hz (Wang, Wang et al. 2006), although peaks are recognised in low (6- 15Hz), medium (15-40Hz) and high 40-60Hz frequency bands (Regan 1989). SSVEP response is strongest in the brain's visual cortex which is located in the occipital lobe of the brain, across the back of the head. With higher frequency SSVEP stimuli, advanced signal processing methods (such as the Hilbert–Huang transform) or averaging over multiple epochs of EEG are required to enhance the signal and improve the accuracy. Also, it is much easier to generate precise flickering at lower frequencies as the computer has fewer tasks to complete over the same period of time. In particular the frequency range around 13Hz is considered a suitable choice, with studies reporting 13Hz to elicit the highest amplitude response (Herrmann 2001, Wang, Wang et al. 2006) with others finding similar results from frequencies nearby, such as 10Hz and 12Hz (Kluge and Hartmann 2007).

Interestingly, flickering frequencies below 26Hz are known to induce feelings of discomfort in users, and one method prescribed to overcome this is to increase the duty-cycle of flickering (i.e. increasing the ON time and decreasing the OFF time during one cycle of the wavelength),. In their study Lee, Yeh et al. (2011) found that when increasing the duty-cycle of flashing not only provided greater visual comfort but also attributed to an increase in the corresponding amplitude response was observed. SSVEP stimuli where duty-cycle can be adjusted to suit individual user response are realised further on in chapter 5. It is worth noting that icon flickering at low frequencies can pose a risk of inducing fits to a small proportion of epilepsy sufferers. All users of the SSVEP BCMIs in this thesis were vetted for their suitability, and participants of the SSVEP experiment were informed of the risks in-line with Plymouth University's ethics committee recommendations.

3.2.1.3 SSVEP stimulus hardware

Historically SSVEP stimuli have been developed for computer screens (firstly CRT then LED, LCD, TFT) and LED lights, aside from rare instances such as the first known SSVEP system which employed fluorescent light (Calhoun and McMillan 1996). Designing SSVEP stimuli for computer screens or LEDs requires technical considerations that relate to the properties of each device, such as refresh rates, the available processing power and icon brightness. The task of rendering stimuli on computer screens is relatively straightforward, however generating real-time flickering at accurately consistent speeds is often hampered by operating systems that are not designed with graphics rendering as one of their primary concern. This notion is acknowledged by Cecotti, Volosyak et al. (2010) in their study of rendering SSVEP on LCD computer screens. In a separate review of the literature Zhu, Bieger et al. (2010) report that LED based stimuli generates the strongest amplitude response and with the best SNR. This is predominantly due to the precision available when controlling LED behaviour, as rendering takes places externally from a PC, and LED's inherent smoothness when flickering between ON and OFF states. Developing LED based stimuli was beyond the scope for the first BCMI developed in the project (the *Flex* BCMI), but LEDs were adopted later in the research to help improve SSVEP accuracy (chapter 5 onwards). In keeping with developing a portable BCMI for laptop PCs the *Flex* BCMI uses a standard LCD laptop screen (from a late 2011 model Macbook Pro 13-inch) for displaying the visual stimuli. The *Flex* BCMI uses four flickering icons, a decision primarily driven by the size of the laptop screen, but this does not confine control to four fixed mappings, as controls are dynamically re-assigned throughout the piece. A new stimuli unit is presented in chapter 5, again with four icons, but this is expandable whereby multiple units can be combined together to provide more SSVEP channels (in multiples of 4). The units use LED flickering stimuli to improve the SSVEP response available from icons generated on a computer screen. A technical report of the unit is provided in section 5.3 and the unit is the subject of an experiment outlined in

section 5.1, which informs the design of the multi-user SSVEP BCMI *Activating Memory.* The units are also used for SSVEP control with the hybrid BCMIs in chapter 7.

3.2.1.4 Incorporating EEG Feedback in SSVEP stimuli

The SSVEP visual interface employed by Miranda, Magee et al. (2011), incorporates EEG feedback into the visual stimuli and this contributes to a user's feeling and understanding of control, in line with the definition of BCI (Wolpaw and Birbaumer 2006). This is particularly useful for two reasons. Firstly, in order to maintain user attention to stimuli feedback is presented as close to the stimuli as possible. If SSVEP success or real-time amplitude feedback is presented on a display separate to the stimuli a distraction is created that can impede user control. Secondly, incorporating visual feedback as part of the stimuli allows for a user to improve their self-regulation with real-time updates on their ability to elicit positive SSVEP response and control amplitude.

To achieve visual feedback in the *Flex* BCMI a coloured ring around the stimuli icon increases in size and in brightness relative to the amplitude of the corresponding SSVEP frequency. A ring begins to appear on-screen once positive SSVEP is detected. Figure 13 shows the stimuli and feedback GUI for the *Flex* BCMI. Here, four icons corresponding to four SSVEP channels are displayed using reversing checkerboard patterns. The SSVEP frequency corresponding to the icon on the left hand side is the current active channel. The outer ring indicates the strength of the amplitude response, approximately 75% of the maximum value in this figure. A second, but more passive element of feedback is also provided. Stimuli icons are presented within images relating to musical mappings. The use of Greek characters is an arbitrary choice, but to the user they represent music control options, where the correlation between symbols and mappings can be learnt either through practice or by updating the symbols to have more musical relevance. Although not implemented in *Flex* the interface can be adapted so that symbols in the interface can also change to reflect that a mapping change has taken place, as well as what the new

mappings mean. This is useful for when users are not familiar with mappings, perhaps by a lack of training. This is the case with both the *Activating Memory* and *A Stark Mind* BCMIs, presented in chapters 5 and 7 respectively, where symbols have a more direct association to the musical mappings.

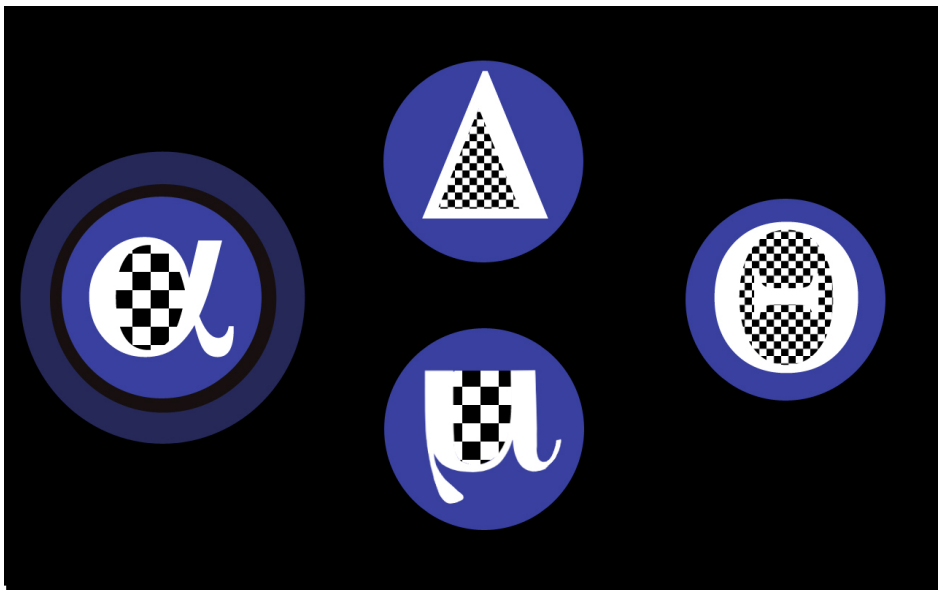

Figure 13. SSVEP stimuli and feedback visual interface for the *Flex* BCMI. Note the visual feedback ring on the left icon, indicating ~ 75% amplitude.

3.2.1.5 SSVEP stimuli colours and patterns

Zhu, Bieger et al. (2010) identify three methods of generating SSVEP stimuli; light stimuli, single graphics stimuli, and pattern reversal stimuli. Light emitting components, such as LEDs or florescent lights, are modulated at a consistent frequency to generate light stimuli. These are external to a computer system and require dedicated and independently configured hardware. They also require additional bespoke functionality to synchronise with EEG data to provide integrated visual feedback, as well as any visual images (such as the aforementioned symbols) to represent mappings.

Both single graphics stimuli and pattern reversal stimuli can be presented via a computer monitor. Single graphic stimuli are generated by the oscillation between two colours at the SSVEP frequency. Icons used in pattern reversal include checkerboards and lines where

two patterns (commonly black and white or red and green) alternate back and forth, again at the SSVEP frequency (Ng, Bradley et al. 2012).

Rendering single graphics or pattern reversal stimuli on computer monitors presents issues that can affect performance of the stimuli that results in the systems inability to positively detect user gazing. Again, flashing rates need to be precise and consistent to elicit a strong SSVEP response. A flickering frequency that deviates from $f0$ either dynamically during flickering or at a consistently different frequency will not induce a strong SSVEP response in EEG, or produce any positive correlation at all. This was observed during early development of the *Flex* BCMI where an older laptop struggled to robustly display single graphics flickering stimuli due to the limitations of the graphics card and an operating system that does not prioritise graphics routines. In addition to this, the issue of flickering stability is exasperated when multiple stimuli are presented. The processing load swells and inconsistencies resulting in dropped frames or lags become more likely. Finally, the refresh rate dictates the stimuli frequencies that can and cannot be used. The refresh rate is the speed at which the display updates its buffer, and on-screen changes on screen cannot be made in-between these updates. Therefore the rate of flashes in both single graphics and checkerboard reversal requires dividing icon onset instances into integers of the screen's refresh rate (Mehta, Hameed et al. 2010), to guarantee the presentation of all flickers on screen.

An important distinction between these two methods of stimuli is that where single graphics icons require two alternations per cycle, pattern reversal requires only one (Zhu, Bieger et al. 2010). The screen of the *Flex* BCMI laptop has a refresh rate of 60Hz, which dictates that screen updates can only occur at multiples of 16.67ms (1/60), and this is equal to one frame. A 12Hz flicker occurs at a rate of 5 frames (or 83ms, where 5 x 16.67ms = 83ms). A single graphics stimuli with a 60Hz screen refresh rate completes one full cycle with two alternations every 5 frames, for example with the alternation at frame 3 as shown in Figure 14. Pattern reversal stimuli would require only one alternation over

the same period, i.e. every 83ms, to elicit SSVEP at the same frequency. Creating stimuli using a frame-based encoding method, as proposed by (Wang, Wang et al. 2010) is a useful method of working within the constraints of the display hardware. As shown in Figure 15 there are 50% fewer alternations required per cycle using the pattern reversal method. This reduction diminishes the graphics processing and provides a more stable rendering technique for the laptop in the *Flex* BCMI. The checkerboard pattern is also illustrated in the *Flex* GUI shown in Figure 13.

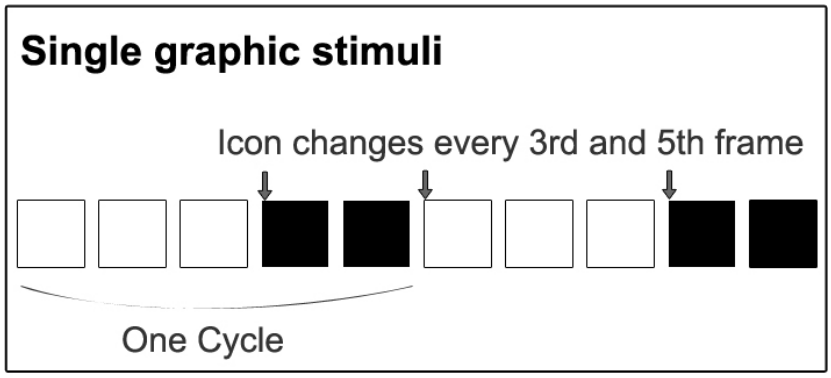

Figure 14. Single graphic icon flickering at 12Hz.

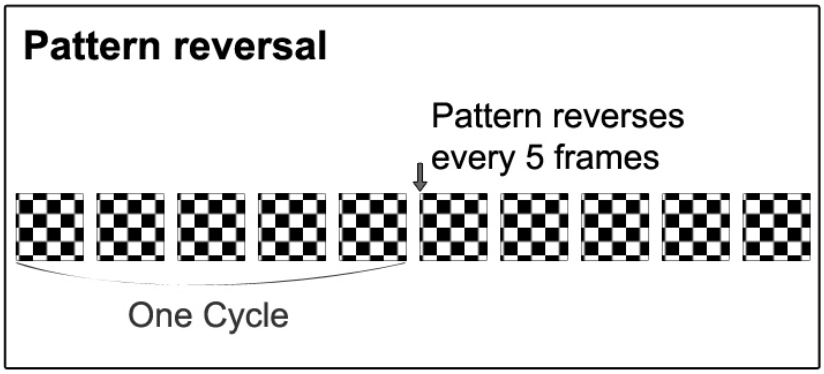

Figure 15. Pattern reversal icon flickering at 12Hz.

Processing of visual information is widely considered to take place in the brain's parvocellular and magnocellular neural pathways (Van Essen, Anderson et al. 1992, Zeki 1993). The first processes colour, and the form of vision, i.e. the spatial information of what it being seen. When combining multiple flashing icons on a display it is quickly

apparent that a number of factors play a role in affecting both the strength of SSVEP response, the ergonomics of using the interface, and the comfort of the user. These factors include icon intensity, the spatial frequency between icons, the distance between the user and the stimuli and the size of the icons and the patterns they contain. Ultimately, an interface should avoid the presence of other icons affecting the user's ability to generate maximum response from the icon being attended to. Arakawa, Tobimatsu et al. (1999) reported on the effects of spatial frequency between stimuli on the harmonic content of SSVEP information and found that differences in spatial frequency can affect amplitude response in these areas, as well as a notable correlation of density with amplitude. A study by Ng, Bradley et al. (2012) also highlighted the factors outlined above, determining that as stimulus size increases and proximity between icons decreases, SSVEP response improves. Interestingly, their study also reported that against user tests no preferred or 'magic' frequencies stood out; there were no results to suggest that certain frequencies performed better than others in their range between 11.3Hz – 23.3Hz, which differs from the SSVEP studies discussed previously. The 13" display in the *Flex* BCMI offers a limited area for presenting icons. This, combined with the processing limitations in mind, informed the decision to use four icons, flickering at low frequencies between 6Hz - 10Hz.

3.2.2 Measuring affective states from EEG

Chapter 6 reports on investigations into affective responses to music and creative applications of such measures in real-time BCMIs. The research acknowledges two key attributes for detecting levels of affect in EEG, arousal and valence (see section 6.2.1).

3.2.2.1 Method

To measure brainwaves unobtrusively in a live performance environment a minimal number of electrodes is desirable. When detecting affective measures in the *Affective Jukebox, The Space Between Us and A Stark Mind* BCMIs (see chapters 6 and 7) EEG is measured with electrodes placed across the prefrontal cortex using the international

10/20 standard, across positions AF3, F3 and A4, F4 with reference electrode at position Cz and ground electrode at FPz. To determine levels of arousal the ratio of alpha band power (which is inversely proportional to increased brain activity) and beta band power, is measured which is associated with increased alertness and cognitive processing (Sammler, Grigutsch et al. 2007), and has also been linked in other studies to an increase in arousal, separate from valence (Sebastiani, Simoni et al. 2003, Aftanas, Reva et al. 2006), as shown in equation 1. Valence is measured as the balance of activation levels in both bands across the left and right hemispheres, shown in equation 2, in order to indicate a difference between a motivated approach or a more negative, withdrawn mental state. This is the approach validated in a previous study by Ramirez and Vamvakousis (2012).

$$\frac{(\beta AF4 + \beta AF3 + \beta F4 + \beta F3)}{(\propto AF4 + \propto AF3 + \propto F4 + \propto F3)} \quad (1)$$

$$\frac{(\beta AF4+\beta F4)}{(\propto AF4+\propto AF4)} - \frac{(\beta AF3+\beta F3)}{(\propto AF3+\propto F3)} \quad (2)$$

EEG is pre-processed using a 50Hz notch filter to reduce mains hum, and artefacts caused by muscle movement or interference are removed by segmenting incoming EEG into epochs of samples (50% overlap; Hanning window) and rejecting those that are clipped above a threshold of +100 μv. This is designed to minimise the effects of movement that are likely to occur, especially during a performance. Alpha and beta band power is extracted by applying 5th order bandpass filters where each sample is squared and averaged over consecutive samples with an epoch length of 128 samples. As we are interested in measuring the mood response to music currently being listened to, values of spectral power are normalized across a window of a pre-specified duration. This allows time for the listener to familiarise with the music and then settle towards an overall affective response. This method is useful to counter the known effect of diminishing arousal over time as subjects familiarise themselves with the stimuli and the environment

(Dillman Carpentier and Potter 2007). A threshold-based classifier is trained to adapt to individual user responses during a calibration phase that is undertaken at the beginning of every interaction with the system, in line with previous studies by (Sammler, Grigutsch et al. 2007). The calibration phase measures responses at the outer limits of the model against the musical stimuli. The system contains an array of musical sequences, each with an intended arousal and valence value. A musical sequence is selected by a transformation algorithm, which maps a user's EEG arousal and valence measure to a corresponding musical sequence or to a set of sequences, across a 2D space – explained in chapter 6 (see Figure 33).

3.2.3 Motor imagery through ERD

In addition to SSVEP control and affective response a third active control method is incorporated into the BCMI used for *A Stark Mind* (see chapter 7). In the hybrid BCMI in this thesis, a two-state, positive/negative control is utilised during SSVEP gazing as an extended control option, as a switch that can be used to add an extra option to an SSVEP choice, if the two methods are performed simultaneously. For example, when SSVEP is used to select a specific visual pattern for the string instruments to play the motor imagery extension might allow for the hybrid BCMI to select either the viola or the violin.

3.2.3.1 Method

The means to obtain a measure of kinaesthetic motor imagery strength ERD is detected by extracting the alpha band-power over the left motor cortex, which is contralateral to the right hand. EEG is measured at electrode positions T7, C3, FC3, and CP3 over the top left hand region of the scalp, with a reference electrode at Cz and ground electrode at AFz. By inverting the signal performing kinaesthetic motor imagery of the right hand (i.e. imagining squeezing a ball in the hand) creates an ERD which is detected as a decrease in the alpha band power in this region (Daly, Williams et al. 2014). The imagination of relaxing has the opposite effect in increasing alpha band-power. The alpha band power

across the electrode channels is averaged, and a threshold-based classifier is used to establish whether ERD is being performed or not. The signal is scaled by a constant, derived from an initial training phase per user, to determine individual response and mapped to a two state ON/OFF control.

Again, data is pre-processed in Matlab with a low pass filter to remove DC offset and a notch filter to reduce mains interference at 50Hz. The software measures mean values of alpha power within 3-second windows using an FFT filter with 1-second overlapping windows for continuous ERD detections. An on-line threshold classifier is used to determine a positive or negative state, representing imagined motor imagery or relaxation, respectively. In the hybrid BCMI for *A Stark Mind* (chapter 7) states are accepted only when positive SSVEP has been detected.

3.3 Implementing the Brain-computer music interface

The main tools used for BCMI development have already been acknowledged in section 1.3. Where the hardware records EEG data, the software tools contribute to three main elements of a BCMI, each performing a specific role; EEG analysis, transformation algorithms and the music or visual engine. The signal path of raw EEG signals and control data that is sent between each task is shown in figure 16.

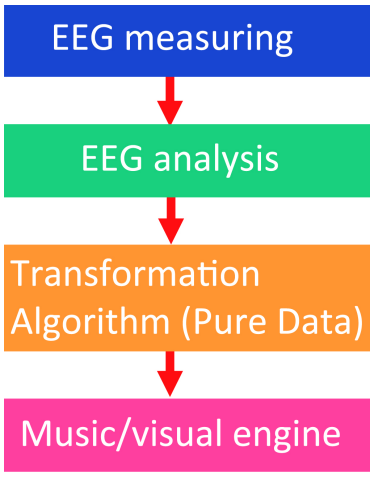

Figure 16. Signal path of raw EEG signals and control data in the BCMIs of this thesis.

3.3.1 EEG analysis software

EEG signals are analysed in Brainbay for the *Flex* BCMI in chapter 4, and in Matlab for the other BCMIs. Both Brainbay and Matlab offer real-time analysis and application prototyping environments suitable for EEG analysis. The Matlab Simulink extensions for g.tec EEG hardware were used for the BCMIs documented in chapter 5 of this thesis and onwards, which included pre-defined objects and customisable paradigms for realising real-time projects. Data, once processed, is transmitted from the EEG analysis software to Pure Data either via MIDI (Brainbay) or OSC (Matlab).

3.3.2 Transformation algorithm development in Pure Data

Pure Data is an open-source programming environment for developing real-time audiovisual projects. Objects can be programmed to perform functions that process streams of data as they pass through a patch from top to bottom, as shown in Figure 17. Using Pure Data EEG signals received from Matlab can be integrated with music and visual performance pieces. For the BCMIs, rule-based transformation algorithms are developed in Pure Data to scale EEG signals for use as control ranges commands that are either mapped to music or graphic control parameters within Pure Data, or sent to external programs or devices either on the same PC or across a *local area network* (LAN) via OSC. The Pure Data visual extension GEM provides the toolkit for developing the visual interface for the *Flex* BCMI (shown in Figure 13), and for the graphic interface used in *Activating Memory* (shown in Figure 30) that display the dynamic electronic score. In both instances, the interfaces respond to the EEG-based mappings to provide visual feedback to users.

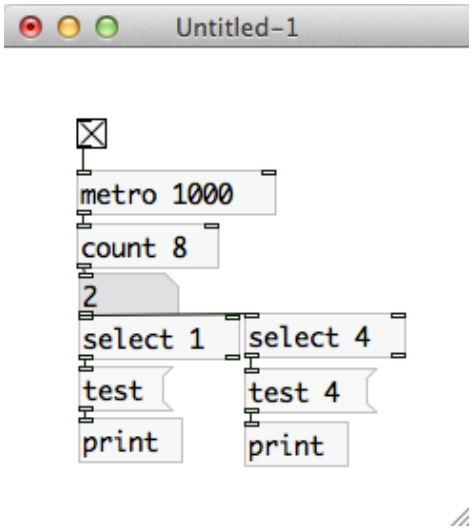

Figure 17. A simple Pure Data patch. Control passes down through the objects through the connections running from top to bottom.

3.3.3 Extensions to external applications and platforms

Pure Data is suitable for interfacing EEG signals to music making tools and other programs within a BCMI because it supports a range of data protocols, is cross-platform and open source. Integra Live and Resolume are used in two of the BCMIs, and their environments are manipulated through the control mappings transmitted from Pure Data. Integra Live is built on Pure Data's audio DSP engine and provides a practical GUI for hosting audio tools that have been developed in Pure Data. Resolume is a performance environment favoured for its *visual jockey* (VJ) capabilities. Video clips and generative visual patterns can be played and manipulated with a range of powerful effects. Essentially the transformation algorithms developed in Pure Data for the BCMIs in this thesis allow for control to be sent to a vast range of interactive software and hardware platforms, both for and beyond the realm of audiovisual control. For example, Pure Data also interfaces with the Arduino platform in real-time, via BCMI control, for performances of *Activating Memory*. More information on the Arduino setup is provided in section 5.2.

3.4 Conclusions

SSVEP, affective measures in EEG and motor imagery form the basis of the BCMI systems presented in chapters 4 – 7.

The SSVEP active control method outlined in section 3.2.1 provides the starting point of enquiry for the BCMI system in chapter 4. Particular consideration is given to issues affecting BCI performance including stimulus rendering, stimulus frequencies, and SSVEP detection. These issues are explored further in chapter 5 towards improving aspects of the SSVEP method adopted. To investigate a secondary method of control alongside SSVEP measuring affective responses to music is deemed appropriate, as it requires no added effort from a user. Chapter 6 provides a study of affective responses to music and presents two BCMI systems that explore this theme. A BCMI that successfully combines both SSVEP and affective measures is presented in section 7.2.

Motor imagery, does not rely on external stimuli and requires a relatively simple mental task. These factors make it a suitable candidate for simultaneous use with SSVEP as there is potential for both methods to be consciously controlled, simultaneously. The BCMI system presented in section 7.3 utilises motor imagery, SSVEP and affective response in a unique BCMI with many-to-many mappings from 3-dimensional control.

3.5 Summary

This chapter provides the technical background to the body of work research presented in the successive chapters of the thesis.

An overview of the three EEG control methods applied in this thesis is given; SSVEP, affective state detection and motor imagery control. The signal flow and major components of the generic BCMI used throughout the thesis has been illustrated, although certain elements differ throughout the development of progressive iterations, which will be discussed in chapters 4 - 7. A brief overview of the software platforms used for BCMI development has been given to provide the reader with a technical foundation for replicating any of the BCMIs documented in this thesis.

Chapter 4: Development of a portable SSVEP BCMI for live performance

This chapter presents the initial research and development towards building a portable and more accessible BCMI system than those discussed in chapter 3, for active control over electronic music. Issues of optimising elements of a BCMI are examined, in particular the importance of EEG accuracy with regards to the stimuli used to generate SSVEP response.

A new BCMI is presented, one that combines a consumer level EEG headset and two laptop computers. The bespoke software and its functionality are outlined giving an overview of how the system performs in a live concert scenario. The performance piece Flex *demonstrates how a BCMI can be used for controlling and manipulating a quadraphonic electronic music composition. The musical design and mappings of* Flex *are discussed in light of the control available with this BCMI and the aesthetics of performing with neurotechnology.*

4.1 Introduction

This chapter presents a new BCMI system designed for active control in live electronic music performance. The primary objective of the BCMI is to provide control over electronic music parameters, using affordable, accessible, and portable equipment. In addition, a development aim of this first BCMI is to replicate the functionality of the BCMI used for *The Warren*, scaling down the components from a high-specification desktop computer setup to laptop PCs, using less costly EEG measuring equipment, and using free, open-source software. The artistic aim is to use the BCMI for a live performance that can engage an audience, whilst acknowledging the limitations of performing with BCMI technology. These aims are motivated by a desire to see whether a robust BCMI system can be developed using low-cost tools, in an effort to promote accessibility to the field of BCMI, and to promote the use of BCMI within the wider computer music field.

To briefly recap, *The Warren* demonstrates how SSVEP can be used as a sole source of control to perform electronic music, live on-stage. Both the composition and mappings are designed to align with the limited control on offer, through four SSVEP channels, and explore the creative possibilities available. The piece also exemplifies how BCMI can be used to replace other digital music interfaces, especially those associated with performing electronic music.

The BCMI used for *The Warren* consists of a Windows desktop PC with two monitor screens, an upgraded high-performance graphics card, the Mindpeak Waverider Pro EEG system (brain cap, electrodes, amplifier and digitiser, EEG processing software), a separate laptop, and a musical engine built using Max for Live[14], a programming library for the Ableton music production platform. The visual stimuli for generating SSVEP response was built in Matlab, by John Wilson, a PhD candidate at Essex University. Because one of the

[14] https://www.ableton.com/en/live/max-for-live/

main factors that determines successful SSVEP control is the accuracy of stimuli's flickering speeds, an expensive, high performance graphics card that was able to process updates accurately was used.

To summarise, the BCMI for *The Warren* was bulky, difficult to transport, it used expensive EEG hardware outside of many musician's budgets, required a medley of paid for commercial software licenses for platforms and considerable bespoke customisation. Because of the desire to take BCMI research out of the laboratory and into more practical music settings, for the new BCMI system I was keen to use portable laptop computers and EEG systems with wireless electrodes. In response a new BCMI for electronic music performance, specifically for the piece *Flex,* developed in 2013, aims to address these limitations in the ways summarised as follows:

- Portability

As mentioned, *The Warren's* BCMI ran on a desktop PC for EEG processing and classification. A separate laptop PC hosted the music engine and EEG was recorded through a sizable hardware amplifier. Transporting all of this equipment to concert venues is problematic due to the volume and weight of all the equipment and necessary cables. However, scaling down computing hardware that is more convenient to transport creates issues where smaller and less powerful equipment may not be capable of the processing required. In the *Flex* BCMI 2 laptop PC's are used, one laptop for presenting the visual stimuli and conducting EEG processing and a second laptop for hosting the music engine. A more affordable wireless EEG device that streams EEG data to a PC via Bluetooth, replaces the Waverider EEG setup. However running efficient SSVEP visual stimuli without a suitably efficient graphic card causes difficulties, again, this is discussed further on.

- Cost of EEG hardware

The hardware and software costs of the *Flex* BCMI are approximately £2,000 (at the time of writing), a financial saving of 66% when compared with the BCMI used for *The Warren*. Although particular issues arise from the use of cheaper components, this is large step towards designing cheaper BCMI systems.

- Open-source tools

In a conscious effort to engage with promoting free, accessible and customisable tools that can exist outside the bounds of commercial interests, software using only open-source environments was developed for the *Flex* BCMI. It is perhaps worth noting, however, that open-source software does not equate to easier implementation or better performance, however interoperability between platforms with open-source software is on the whole improved.

- Performing live with BCMIs

Performing live with EEG has inherent limitations, due to the fact that the operator, or BCMI performer, must remain motionless to exert BCI control. This can have a polarising effect on members of an audience as although the sight of a BCMI can draw curiosity, it is impossible to comprehend the intentions of the user without some element of communication. There are two aspects that *Flex*, and the BCMIs in the remainder of this thesis attempt to address:

1. A live musical performance controlled by brainwaves is not a common experience for most audiences. To help an audience engage with such a format it can be useful for the essence of control to be communicated to an audience. BCMI technology is quite an exclusive interface, mainly because most audiences will not already understand the processes involved and watching someone sitting in front of a computer screen whilst music resounds can be very confusing for some audience

members to understand, and therefore enjoy. To someone with no prior exposure to a BCMI, without an explanation the leap of faith required to move past believing in the control and enjoying the music and the possibilities of BCMI can be difficult to attain. This element of communication does not have to be in-depth, and does not have to apply to every aspect of control during a performance, but in order to provide a sense of the link between the how the brain is linked to the music it seems important to provide some kind of explanation (in as universal a way as possible) in an otherwise non-physical performance where expression is extremely limited. This approach is not a million miles away from how music composers aim to draw audiences into their compositions by first introducing musical themes, or motifs, to build a foundation for expansion once an audience is engaged. Themes are first introduced in their simplest form, before being repeated and then transformed before the piece can take off in different directions. One of the most well-known and simple examples of this is Beethoven's Fifth Symphony, where the four-note motif (duh-duh-duh-duuuuh) introduced at the start of the piece is extrapolated and modulated throughout the rest of the movement. This approach draws the listener into the sound world, and once in, holds their full attention and imagination, as they too are taken off in different directions. Likewise, a simple introduction of BCMI control presented to an audience early on in a performance is a very useful way of mirroring this idea.

2. Given the physical and gestural limitations of BCMI control there is an interest to design performances that are visually engaging. There are areas of live music control where an audience can expect no visual element to the performance whatsoever. The worlds of acousmatic or electro-acoustic music are prime examples of this. However, when demonstrating a new interface, especially one as exciting as using BCMI, an audience's expectation is likely to be high. And although most audience members will revel in the notion that brainwave control can mean

control without physical movement, it can be rather dull to watch for extended periods of time. This raises two questions that are explored in this thesis. First, can visual engagement be achieved by amplifying the otherwise visually minimal elements of control taking place? And second, can BCMI performance be extended to include separate elements with more visually engaging aspects? *Flex* focuses on the first of these two questions with later aspects of this thesis addressing the second.

Performances of *Flex* aim to highlight the indivuidual, and isolated efforts of the BCMI performer by directing the audience to the performer's facial expressions through the staging of the piece.

4.2 Practicalities of SSVEP for BCMI

As previously addressed, medical grade EEG systems are expensive, bulky, and as such inefficient to transport and setup. In recent years, headsets aimed at the pro-sumer gaming and neuro-entertainment market (which is a fusion of proclaimed 'brain-training' and meditation systems coupled with real-time EEG feedback that claim to help improvement in both of these areas) have emerged. Companies such as NeuroSky, Muse[15] and Emotiv offer affordable EEG headsets and software platforms, but often at the expense of electrode channels and limited interoperability with external programming tools. More importantly they offer poor accuracy in EEG acquisition in comparison with more expensive platforms (Liu, Jiang et al. 2012). On a more positive note, these devices offer a step into the world of approximating brainwave information content for creative application, especially for those with low budgets. If one of these devices were to be chosen as a platform for BCMI development then attention needs to be paid to factors that can help minimise issues with signal accuracy, such as designing robust stimuli, using a suitable room environment and the selection of EEG processing methods. The *Flex* BCMI uses the Emotiv EPOC headset, a device at the higher end of the pro-sumer range. Although Emotiv is a proprietary system, the platform is supplied with an *Application Programming Interface* (API), at an extra cost, which allows for integration with external applications and devices. As such, *Flex* is designed to demonstrate the effectiveness of using this kind of device for SSVEP control over music.

4.2.1 SSVEP accuracy and response time

It is appropriate at this stage to expand on accuracy, in the context of active BCMI control. Accurately detecting user intent is a primary concern in measuring EEG responses for active control and this provides the foundation for designing the user experience through

[15] http://www.choosemuse.com/

musical mapping strategies that, for example, either rely on accurate control or have to manage a low level of accuracy whilst still resulting in enjoyable musical outcomes.

Accuracy in active control has two key features that are also crucial for control over music. They are:

1. **Reliability**. A percentile measurement of accuracy helps determine the performance of a BCMI system. For example, if over 10 trials a system can successfully detect 10 SSVEP choices made a user makes then 100% accuracy is achievable. SSVEP accuracy usually lies between approximately 80-96% (this figure is discussed further in section 5.2.1). Therefore, transformation algorithms and their associated musical mappings need to take any error rate into account, as an SSVEP BCMI that has less than 100% accuracy cannot wholly rely on anticipating a guaranteed positive SSVEP detection at any given time.

2. **Speed**. For real-time control, or as close to real-time as possible, how fast the system detects user choice determines how quickly musical changes can occur. Delays in detection can arise from signal processing functions that take average windows of data over a specified window size. For example, processing an incoming EEG signal with a Fast Fourier Transform (FFT) returns a value every *n* samples or seconds (*n* increases proportionally to window size). The smaller the window size then the quicker the result is returned, but with a larger window comes greater spectral resolution and a better signal-to-noise (SNR) (Wilson and Palaniappan 2011). An optimal window size that takes into account the response time but also provides an acceptable degree of accuracy is therefore desirable.

Two particular issues have a major effect on accurate measures within EEG signals:

1. ***Signal-to-noise ratio* (SNR)**. Noise is an inherent factor when determining EEG signals. Electrical activity from the brain lies in the region of microvolts by the

time it is detected through the skull, meninges, layers of skin and hair. Aside from these physical attributes that degrade the signal, artefacts from muscle movement, localised static sources (including users' hair) and other electrical equipment also generate electrical current that can be detected by EEG measuring electrodes, and subsequently interfere with the desired signal. Amplifying an electrical signal of such a low voltage level also amplifies any noise that is picked up from these external sources, and from on-going background EEG activity that spills into the detected brain regions and frequency ranges being measured. There are a number of approaches to handling noise within EEG signals. A common strategy is to use multiple electrodes across a particular region to provide an average reading (Liu, Jiang et al. 2012, Zhang, Xu et al. 2012). This takes into account electrode channels that contain noise where the interference on one channel can be offset by the consistency of others. However, this is problematic when measuring EEG across the visual cortex with the Emotiv headset as there are only 2 electrode positions in this area. In BCMIs discussed later in this thesis where electrodes need to be placed individually into brain caps a minimal electrode approach is adopted to reduce setup time and help reduce discomfort when applying the headset and electrodes, especially when using electrodes that require skin abrasion and the application of conductive gel. Another common method is to reject epochs of EEG where noise is easily discernable (commonly where the voltage level is far above what is considered a standard baseline). This can help smooth readings where noise results in a signal above a certain threshold, but this can cause problems in real-time systems where noise is picked up during a positive control signal. Reducing noise is therefore an important concern when designing a BCMI system for stable control as high levels of noise can also create false positive detections.

2. **False positive detections.** False positive SSVEP detections occur when the system interprets a high amplitude measure over an SSVEP frequency as a positive SSVEP command, when the user is not actively attempting to exert control by gazing.

False positive values can are difficult to manage as they are commonly generated by spontaneous noise in EEG, and this is unpredictable. When good quality electrodes and correct signal processing is applied then noise from external sources is the most likely contributor of false positives and this can be reduced environmentally. Two general principles are applied to help offset false positive values in this research. The first is to reduce overall electrical activity from the immediate local environment. This includes creating distance or separation from mains power, lighting, mobile phones, and electrical cabling not touching or running in parallel with EEG electrode wires. The second principle is to calibrate the SSVEP classifier to a user's response, adjusting the classifier to only respond to stronger SSVEP signals. This does not eliminate the intrusion of strong levels of noise, but helps reduce low-level noise, which is generally more common.

Having a high level of accuracy is desirable for providing a high level of control over music as it allows for precision that can be mapped to music parameters over a range of levels from micro-level detailed parameters to macro-level arrangement or structural parameters, without the introduction of musical errors. Poor performance with regards to the above two issues can result in input commands not being detected, incorrect input commands being detected, a slow system response to input commands, and these ultimately result in a poor user experience; again, when mappings are not successfully, the *feel* of the interface suffers. For the *Flex* BCMI there are discernable limitations of the Emotiv device to consider, in particular the accuracy of detecting SSVEP. Two further approaches to managing this were adopted. The first is to develop a robust visual stimulus with the processing power and display option available. The second approach is to seek a form of creative exploitation of poor accuracy, and *Flex* attempts to harness this problem and turn it into a creative application in itself. This is undertaken through the mappings of *Flex* which go as far to reduce the importance of consistent accuracy by frequently randomising mappings to create a game for the user, whereby controls are hidden and

need to be found and managed in order to successfully play the piece. As a result incorrect detections (through user selection) are going to be made regardless of false positives, which in turn can be used to help the user find control.

4.3 System design for *Flex*

The elements that make up the *Flex* BCMI are similar to the generic BCMI components outlined in section 2.4, earlier in this thesis. For *Flex,* the system is customised to suit the functions and tasks of performing the piece. Figure 18 illustrates the system and the interconnectivity between the individual components. The system centres around two laptop PCs that distribute the computational processing required for the BCMI. This is important for maximising the efficiency of two processing, rendering flickering icons on-screen at precise flickering rates, and real-time EEG analysis and processing.

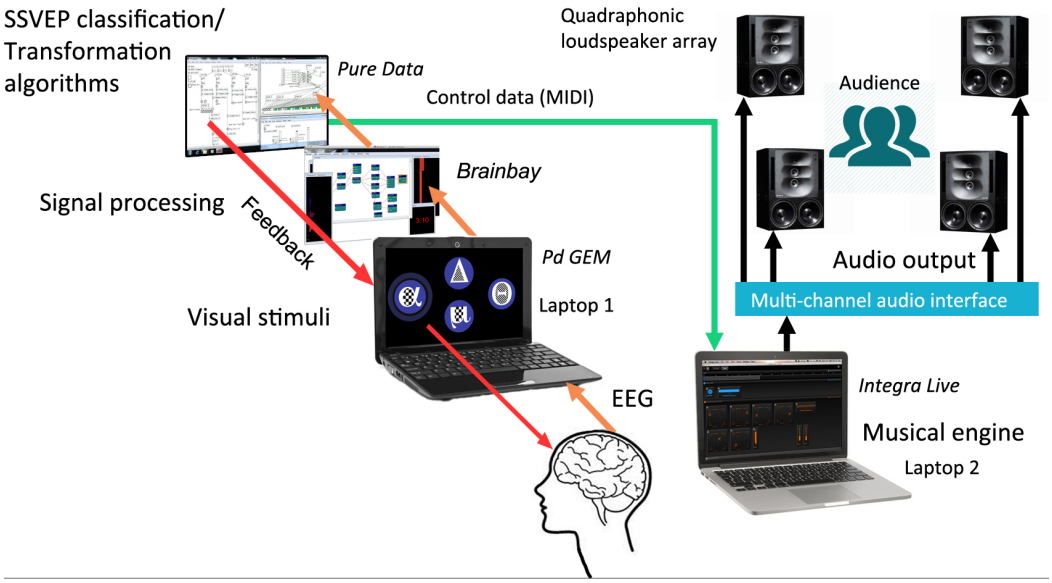

Figure 18. Diagram of the software and hardware components within the *Flex* BCMI.

The *Flex* BCMI consists of the following elements:

- **SSVEP Stimuli**. The GUI containing flickering SSVEP stimuli is displayed on laptop 1. Four reversing checkerboard patterns are displayed at the centre top and bottom, and the left and right of the screen, as shown in Figure 13. The icons are reversed with a 50% duty cycle at frequencies of 6Hz, 7.5Hz, 8.57Hz and 10Hz. The frequencies are all integer divisors of the screen's vertical refresh rate, 60Hz. The visual stimuli was programmed in the GEM environment and allows for control data to generate visual feedback, indicating EEG strength relating to each channel to be received from the transformation algorithm.

- **EEG measurement.** The Emotiv headset measures the performer's EEG whilst they are sitting still positioned in front of laptop 1. The two rear Emotiv electrodes, located at positions O1 and O2, are used to approximate electrical activity in the visual cortex, and are both positioned over the rear of the scalp. The headset transmits raw EEG values via Bluetooth using the Emotiv USB Bluetooth adaptor to laptop 1 for signal processing in real-time.
- **EEG signal processing.** A bespoke object for receiving Bluetooth data from the Emotiv allows for signal processing to be undertaken in Brainbay using the FFT processing method introduced in section 3.2.1. The FFT filters detect the signal strength across the four target frequencies. The FFT power derivatives from each filter are then scaled to MIDI note values (0 – 127) across four channels and are transmitted from Brainbay using MIDI Yoke, a free software tool for routing MIDI signals between programs.
- **SSVEP Classification**. MIDI values are received in Pure Data for SSVEP classification using an online linear threshold algorithm. A bespoke program provides an interface for a user to define their a^{min} and a^{max}, values taken during a short calibration phase. To help reduce artefacts found in the noisy environments where *Flex* was performed it was found to be best to set a^{min} thresholds higher than what would be considered necessary in a controlled environment. This helps to minimise instances of false positive responses triggered by interference. The program allows the threshold values to be stored for future recall by a user and the corresponding control range between a^{min} and a^{max} is scaled across each channel to provide a fixed input scale for the musical mappings.
- **Transformation algorithm.** The mappings within the Pure Data program provide the control over the musical parameters inside the music engine. Each of the four SSVEP control channels is connected to a series of control triggers and ranges in parallel with the arrangement of the music. The music of *Flex* is in two main sections, the 1st (bell) section and the 2nd (guitar) section. An overlapping section,

contains elements of the two combined with some extra sounds and controls, and provides a transition period to help move from one section to the other. Mappings are discussed further in section 4.4.2.

- **Music engine.** The music engine is built in the Integra Live environment and receives control data via MIDI from the Pure Data program. A bespoke Integra Live project connects the control data to musical parameters and allows for input ranges to be scaled further to the necessary music sample playback parameters, real-time effects and surround panoramic positioning. The music engine resides on laptop 2, to spread the overall processing load, and outputs four channels of audio through a dedicated Firewire audio interface to four independent loudspeaker channels creating a quadraphonic array. Quadraphonic playback provides a listener with four channels of immersive surround sound, a front and back pair of left and right loudspeakers. By manipulating the balance of sound between loudspeakers (known as the panorama) sounds can have the illusion of moving across the space in 2-dimensions as well as traversing the edge of the space, i.e. rotation back and forth around the space.

4.4 Flex

This section discusses the performance piece *Flex* with a particular focus on the composition, mappings and live performance aspects.

4.4.1 Overview

The musical composition of *Flex* is designed to demonstrate how a portable, affordable and accessible BCMI can be used to control contemporary electronic music in a live performance concert. *Flex* also adds an element of unpredictability to a BCMI performance through the mapping strategy employed. This unique approach somewhat blurs the lines between active and passive control and presents itself as an interesting way of addressing the concept of control (especially when accuracy is not 100%) to create a creative and flexible music manipulation system.

Appendix 1 contains three supporting files that illustrate *Flex*. 4-channel surround audio files and a stereo mix-down file (where quadraphonic panning is encoded across 2 audio channels) were recorded during a live performance of *Flex* in 2013. A documentary video presents an overview of the system with a demonstration of the interface.

The music of *Flex* is made of pre-recorded sounds and the objective of the performance is to manipulate them in interesting and musical ways whilst directing the arrangement accordingly. The sounds consist of sample sets from three different sound sources. The first sound source is a bell that was struck in a variety of ways and moved within the recording space to create both differences in excitation and spatial positioning. Multiple recordings were captured using a quadraphonic recording technique, using four microphones to capture a front and rear stereo field. Quadraphonic sound is the emulating of a 360-degree sound environment using four loudspeakers positioned at the edges of a square, facing a central point. Quadraphonic microphone recording techniques allow for surround sound recording with four microphone capsules. When the recordings from each

of the quadraphonic microphone channels are directly mapped to the corresponding loudspeaker, an accurate surround-sound effect is achieved.

During performances of *Flex*, the first section contains bell samples that are triggered, either individually or in clusters of pre-set densities. Additional playback controls allow for applying spectral and filtering effects as well as accelerated panoramic movement across the quadraphonic space.

The second section, which is really a short transition period between the first and third sections, uses quadraphonic and stereo field recordings of a fairground. The fairground samples are manipulated using digital signal processing techniques in an attempt to mask their origin yet allow elements of the environment to appear within the sounds. When triggered using the BCMI, the samples play at different speeds and subsequently at different pitches, and these loosely convey the distinctions between the funfair rides that were recorded. The effect of the transition period is to introduce a momentum to the piece through the conflicting rhythmic attributes of the fairground samples, some of which are played as short looped sounds. The previously sparser and more synthetic sounds of the bell, from the first section, begin to intertwine with the more real-world sounding, rhythmic patterns teased out from the fairground recordings. This period acts to shift the piece into a more dense sonic landscape, as the samples of the final section begin to play alongside the bells and fairground, and eventually take precedent.

The third sample set consists of processed electric guitar recordings. During performances of *Flex*, the BCMI controls sample chopping parameters, modulation effects and also for the samples to be layered on top of each other to create a richer palette of sonic textures. Sound diffusion of all the samples, which is the act of spreading the sound across an environment, is done through BCMI control over the quadraphonic panoramic positioning. Inputs are mapped to position and move the samples across the quadraphonic space.

Flex is designed to last between approximately 10 - 15 minutes depending on the how the quickly the controls are found and how they are used. A key aim of the performance is to convey the narrative of the composition whilst attempting to engage an audience through the sound manipulation undertaken by the performer.

The key feature of *Flex's* mappings occurs when the program is initiated, and when controls are assigned to new mappings at the start of the other two stages of the piece (transition and second section), the assignment of the four input controls to the musical mappings is randomised. At the beginning of a performance four specific controls (from the four flickering icons) are known by the performer, and this provides the control for the first section. The mappings from these control channels change during the transition period and again for the second section. However, at each of these three stages in the performance the mappings of the four control channels are randomised. To add further complication to the control there is a chance that the controls will be randomised again partway during each section, via a probability matrix within the transformation algorithm. Through practice the performer will always know the four different control parameters on offer, but they will not know which flickering icon they are mapped to. This allows for control to be given to the performer, but also hidden at the same time. Therefore the performer must ascertain which icon relates to which channel during each section in order to conduct the desired changes.

4.4.2 Mappings

Built-in rules within the transformation algorithm allow for the presence of mappings corresponding to the current sounds being played, but the choice of parameters is selected at random from an array of predetermined functions. Again, a probability matrix determines the outcome of mappings during performance. A probability matrix is useful as it allows for deviation from a set path to be limited by the probabilities. A user, with access to programming the probability matrix, can define the likelihood of randomisation during

sections, and the changing of parameters to suit. From a conceptual perspective *Flex* presents the mind as muscle, using primitive actions, memory and controlled randomisation to replace the physical embodiment of performance more common in music. Control is integral to moving the piece forward but only becomes explicitly known to the performer after they have consciously derived it for themselves from its side effects. As a result of this, the mappings are key to providing the feel, direction and nature of accuracy within the piece, from the micro to macro musical parameters, replacing traditional, physical controllers to manipulate, arrange, synthesise and diffuse combinations of recorded and computer generated sound.

Indeed, there are more mappings available that can be used in any one performance, which helps make every performance different. Control in *Flex* can be difficult to establish, and this brings elements of the unexpected and even the undesirable into a performance. Hidden secondary mappings are also built-in to add elements of surprise, in effect further flexing the rigidity of control throughout the piece. Overall, the mapping system is designed for control to be manageable and, where control becomes lost, it is relatively easy to recover. As such, certain safety features are implemented within the transformation algorithms in order to prevent complete chaos.

Analysing the four input controls available during the one of the two main sections of the piece can help provide a useful assessment of the mappings as a whole. The type of mapping is defined by the musical task, so for example a switch to trigger sample playback is performed by an SSVEP function that sends a command once a value greater than a^{min} has been detected from the corresponding SSVEP input channel. In contrast to increase the amount of distortion effect to the guitar samples in the second section the range between a^{min} and a^{max} is mapped to the input range of the distortion effect, specifically the DRY/WET mix of the effect. For music effects the DRY/WET mix is the balance between the amount of unprocessed signal (DRY) and the effected, processed signal (WET) in the output signal. With a DRY/WET balance of 0/100, 100% of the output signal is comprised

of the effected signal. With a balance of 50/50, the output comprises 50% of the DRY signal and 50% of the WET. This is a useful for blending in the sound of effects and playing music with various amounts of effects added to the sound. Similarly the type of musical control also differs, not just in terms of the specific musical task but also in terms of the structural level. Macro-level controls affect the global arrangement of the piece, for example switching from the first section into the transition. Medium-level controls affect groups of sounds or a series of tasks from one command. And micro-level controls provide direct control over individual samples, effects and pan positioning movements. Triggering a high-level control at the wrong time can result in a totally different performance. Likewise, performing a low level control at the wrong time can result in a sound being played at the wrong time. To avoid these instances, which are highly likely when mappings are randomised, certain safety measures are implemented. For example high-level controls are only available during certain time periods. The flexibility of the piece and dynamic structure afforded by the style of the music also contributes to the effects of major mistakes being minimal. A performer can make many mistakes throughout a performance but most will likely go unnoticed by audience, who will be unfamiliar with the correct arrangement and manipulation.

The issue of managing false positives with *Flex* is also factored in by this mapping strategy. False positive values can at times be useful to help a performer determine the mappings at the beginning of sections, and if further randomisation occurs. They can also add musical expressiveness, as secondary mappings exist during the second section for when positive SSVEP across two channels is simultaneously detected, which is a strong indication of a positive user selection and a false positive value (false positive values appear mostly in this way). This inclusion of false positives in the mappings demonstrates a way of harnessing one of the major issues of the BCMI, and by presenting the lack of control to the audience in musical form and through the expressions of the performer a creative application of such a problem is used to an advantage.

Here, as in Grierson's P300 BCMI (Grierson, 2008), the meaning within SSVEP EEG is applied through the stimuli, and is therefore learnt by the user, even though mappings in *Flex* are randomised. With such an abundant amount of meaningful data *Flex* embeds further layers of intelligent control, as rules built into the computer, that provide deeper complexity. As an example, ordering rules were applied to control specific musical parameters through monitoring the performers' control behaviour. The order in which the performer affects control over the icons, and over *x* amount of control changes, would result in different generative rules being applied. This harks back to Miranda's technique (Miranda, 2005), with the integration of Hjorth analysis and adding intelligent feedback to the system as part of the compositional process.

These principles are adopted in a number of ways in *Flex*, and the inclusion of conditional rules and variations allow for expanding the ways of using amplitude control. For example, in the second section a guitar sample can be played using the derivative measurement of the increment and decrement of one EEG input channel. Alongside this control a second input channel has an integral control to regulate a modulation index relative to the guitar processing; an example of interpolating two different primary controls to manipulate one sound. To add further control within these selection based mappings the three following mapping rules were applied to the four incoming EEG data streams, and used at various times during the piece depending on the required function:

1. **Threshold values**. All four of the brainwave control signals can act as a single selector using mappings for when the amplitude is high or low. Beyond this each input signal can be assigned a number of commands. Control over brainwave amplitude was mapped to a series of functions across a range of evenly spaced threshold values. When the input signal reaches threshold value a command is output. For example, an input signal with a range of 1 - 25 can be treated with the following rule:

```
if input == 5 then play note C2, else
if input == 10 then play note D2, else
if input == 15 then play note E2, else
if input == 20 then play note F2
```

Without further consideration an input signal rising and falling through this range would excite all of the notes on the way up and on the way down. In *Flex* an additional rule of ignoring the input signal when decreasing, i.e. when the user looks away, applies in certain mappings to avoid switching of a feature when the amplitude decreases. The use of timing rules provides the performer with the ability to make specific selections whilst avoiding triggering unwanted commands.

2. **Timing**. The majority of the mappings within *Flex* are led by timing rules. Calculating the time a user takes to complete cognitive tasks allows for an added dimension of control. In the simplified example shown above the speed at which a brainwave increases towards a threshold value would dictate whether the in between mapping rules are accepted or not. This allows the performer to choose how many of the threshold values within one input range to select during any one command. If the time between initial excitation and input signal reaching a value of 15 is greater than X then only E2 would be played. If the time was less than x and more than 1/2X, then D2 and E2 would be played. Less than 1/2X then C2, D2 and E2. In practice the timing rules were used like this alongside the threshold values and also separately on their own. They were mapped to parameters ranging from effects settings such as amplitude, timing, and spectral modulation.

   Further complexity was added through exploiting the features of using timers. A hold-and-release function allowed for a change in control to occur at the point of release. The time between the hold command and the release command being received provided selectable options. When an input value increases, a timer begins until the value decreases. Upon this decrease the value of time is compared against a series of rules. As we have seen during performance the accuracy of

brainwave control is destined to change due to a range of factors. To accommodate this instability when attempting to sustain brainwave amplitude through SSVEP a further time-delay rule monitors the EEG. For example if we define a threshold input value of 5, so that when the input value increases above 5 a hold command is activated. If the input stays above 5 then the hold command stays on, and if the value decreases below 5 it is released. To add some flexibility to this simple hold and release function, a time delay of three seconds is added to the hold function. Therefore if the input decreases below 5 for less than three seconds and then increases to above 5, the hold command remains on. If the input decreases to below 5 for longer than three seconds then the release function is activated. This technique creates a rule whereby an icon needs to be fixated on constantly to generate a command sent to the performance system, akin to the constant attention required to play a sustained note on an acoustic instrument. Deviation from this attention is allowed for a time span of up to three seconds, allowing for the performer to utilise other input gestures to manipulate the sound via different parameters or to control other aspects of the music. To help assist with calculating times during performance a digital clock display was built into the visual interface.

3. **Ordering**. The mappings and structure of the *Flex* were built to allow loose periods for the performer to 'play' the system. Within this it was unlikely that the exact manner in which the controls were used would ever be the same twice. To add a further layer of complexity an ordering rule was implemented that determined musical outcomes based on the order of icon selection. This contributed to elements of musical surprise and quasi-randomness to the piece, as at times it was difficult for the performer to predict these as they were concentrating on other, more direct areas of control.

The level of depth attained within these mapping strategies requires a high level of mental concentration and awareness of time, external and in relation to the music within a

performance. Here the mappings had to be learned, practiced and optimised for system performance and user ability.

When designing mappings for a structured performance piece, as opposed to an instrument or an improvised piece, the mappings need to adapt to the arrangement of the composition and the functions. This reverse engineering type of method of mapping design based on musical function and necessity provides an interesting arena for creativity. As a result, the mappings explored in *Flex* vary at different times during the piece. Instead of summarising these mappings solely in numerical terms, the nature of how the control is governed can be presented in parallel with the Proportional-Integral-Derivative (PID) model proposed by Dean and Wellman (1991). This approach defines control as the effect of the input signal onto the output's value, regardless of the number of parameters connected. Proportional control dictates that output values are relative to input; the output is value X because the input is X. Integral control provides an output value based solely upon the history of the input whereas derivative control gives an output value relative to the rate of change of the input signal.

The piece explores the possibilities of one-to-one and one-to-many mappings using the SSVEP technique similar to *The Warren*. However, control during *Flex* is much more difficult than the control for *The Warren* due to the randomisation factor, and performing commands correctly can take much longer. Taking this into account some generative musical rules are applied to add some controlled variety to the resulting sounds at certain times during the piece. Importantly, *Flex* is not meant to be easy to control. An artistic aim of *Flex* is to remove some of the certainty that comes with direct SSVEP mappings, which creates a greater chance for the arrangement of the piece to differ from the intended structure, which the performer attempts to produce. This differs from other active BCMIs, in particular *The Warren,* and *Activating Memory*, where accuracy and direct control are essential. *Flex* is not intended to be used as an accessible tool for active BCMI use, and it does not demonstrate the potential of direct music control. However, what it does do is

allow for musical variety, chance, and an unpredictability that I wanted to explore as both a composer and BCMI performer. For *Flex*, I wanted to explore what happens when the feeling of control is removed, for two reasons. First, to make both the arrangement and the musical outcome of the piece unpredictable, within the constraints of the mapping rules and composition design. This makes performing *Flex* exciting and challenging for the performer, and also both unpredictability and chance rarely feature in electronic music performance. Second, communicating BCMI control to an audience is difficult for a BCMI performer, and this is something that I observed when performing *The Warren* – audience members found it hard to connect the motionless stance of the BCMI performer to control of the music that was being generated. To counter this, the addition of complexity that can result in a range of positive or negative musical outcomes was necessary to generate feelings of tension, stress, worry, joy and satisfaction in the BCMI performer. With the aid of the stage setting the facial expressions conveying these feeling were amplified as the visual focus for the audience.

Table 6 shows an excerpt of the mappings for the first section, specifically for control over playback of the bell samples. The table shows how the four SSVEP channels are used for control both individually and when combined using an ordering rule to start the beginning of the piece. Icons are not numbered due to the randomisation factor, they are labelled A - D. Music parameters are also defined by stochastic variables to add further controlled variability to the piece. For example, when one of the bell sample groups is triggered the onset times of individual samples are not wholly predetermined. The samples play at irregular times, with onset values picked randomly within a stochastic range. The outcome of certain control combinations can create a chaotic sound within this section. For example, the bell sample groups increase in sonic complexity in relation to their number. When sample group 4 is triggered, along with a high density and a fast pan rotation, heavily distorted artefacts are introduced and the overall sound is unpleasant. The

performer aims to learn these combinations and attempts to avoid such outcomes during a performance.

Channel (arbitrary)	Mapping strategy	Musical control parameters
	Many-to-one An ordering rule is used to start the piece.	Two specfic icons need to be selected, in both cases by input > a^{min} , in the correct order to generate a command trigger The command triggers the playback of bell sample groups
A	One-to-many Timing rules: 1. If input > a^{min} , > 1sec, < 3sec then output = 1 2. If input > a^{min} , > 3sec, < 6sec then output = 2 3. If input > a^{min} , > 6sec, < 9sec then output = 3 4. If input > a^{min} && > 9sec, then output = 4	Outputs of timing rule trigger samples: 1. Trigger playback of bell sample group 2 2. Trigger playback of bell sample group 3 3. Trigger playback of bell sample group 4 4. Trigger playback of bell sample group 5 Move to transition section when output mapping 4 has been triggered twice consecutively.
B	One-to-many Threshold values (only triggered when input is ascending): 1. If input = a^{min} , then output = 1 2. If input = a^{min} + *x*, then output = 2 3. If input = a^{min} + *y*, then output = 3 4. If input = a^{min} + *z*, then output = 4	Outputs of timing rule are mapped to 4 levels of bell density for current sample group. Default density is 0. 1. Density = 1 2. Density = 2 3. Density = 3 4. Density = 4
C	One-to-many 3-state toggle switch triggered when: Input > a^{min}	Diffusion of samples within current bell group: 1. Original sample spatialisation (default) 2. Slow clustering pan movements across 2-d space 3. Fast pan rotations
D	One-to-many 3-state toggle switch triggered when: Input > a^{min}	Switch moves from one output state to another, and applies spectral sound effect and distortion to samples in current playback group 1. No effect (default) 2. Applying spectral filtering effects 3. Apply distortion effects

Table 6. Icon to music mappings for the 1st section of *Flex*. Mappings are randomised so numbering is not necessary.

4.4.3 Performance

Flex was first performed at *Sight, Sound Space and Play,* at De Montfort University in June 2013. Later iterations of *Flex* were performed at the 10th International Conference on Computer Music and Multidisciplinary Research (CMMR), Marseille, France, and at Liverpool venue FACT, in 2014. During performances, the BCMI performer (the author) sits on stage in front of the laptop 1, facing the audience in a darkened auditorium. As mentioned earlier, the only light in the room comes from the laptop screen illuminating the performer's face to the audience. This element of stage design is used to communicate the mental concentration that is required, and convey the successes and failures of control through illuminating facial expressions. During times when the performer fails to follow the correct arrangement, frustration and disappointment is conveyed through their facial expressions, and times when control was found and used to perform certain specific nuances elation and joy could be seen. In a musical sense, loss of control or extreme control choices can result in dissonance and sonic chaos that again communicate the playing of the system. The attempt to exploit the visual limitations of the system, by making the face of the performer the focus of attention, divided audience members' opinion during performances of *Flex*. For example, after one performance at an event attended predominantly by music composers, some audience members praised this element of communicating mental focus. Whereas at another performance, some audience members commented on the frustration they felt by the methods of control not being communicated clearly enough and leaving too much to the imagination. This feedback, although only representing a sample of the audience, indicates that there is still some room for improvement with regards to audience engagement. The notion of not just communicating control but providing enough visual stimulation during performance was taken on board in the development of the BCMIs presented later on in this thesis.

From a BCMI user perspective, performing with the *Flex* BCMI is a combination of fun and high concentration. Musically, the system relies on enough generative rules to provide a dynamic sonic tapestry, one that differs during every performance. On the other hand, the performer is aware of the pressure to find the key controls for directing the arrangement of the piece in the intended manner. If mismanaged, the performance could be cut short by almost a third of the intended duration. Likewise, not finding the controls, either by chance or deduction, extends the length of the piece, until the correct control commands have been received. Hence the facial expressions amplified by the stage lighting are likely exaggerated due to this pressure, but also intentionally in order to reflect how the performer's experience. The removal of the initial mappings for the performer adds an additional element of effort that is required to perform *Flex*, as does accurately performing SSVEP control using the Emotiv device. Where more concentration is necessary through memorising mapping rules (as well as the input selections that do not have associated mappings) the user's attention is subsumed by the BCMI and the reward from finding success is enhanced. When performing *Flex* a user may feel less in direct control than say, when performing *The Warren,* but both the demands for achieving control and the rewards of doing so feel significantly greater.

4.5 Discussion

The *Flex* BCMI demonstrates how a larger, heavier system impractical for transportation to and from musical performances can be scaled down to run on two laptop PCs, using open source software and a consumer level headset. This is a useful and practical solution for performing with brainwaves, but nonetheless it comes at a cost. The signal quality afforded by the Emotiv headset is significantly poorer than medical grade EEG equipment used in earlier BCMI systems. The Emotiv headset is highly susceptible to head movement, external electrical sources and the movement of other people in the vicinity of the user. The accuracy available requires improvement for developing future BCMIs that use active control. This issue adds an additional level of difficulty of control during *Flex* and dictates that certain safety measures need to be included in the transformation algorithms that take false positive values into account. That said, control during performances of *Flex* is achievable, and accuracy appears to increase with training and experience, although the environmental conditions need to be carefully monitored for optimal system performance.

The discrepancy between pro-sumer and medical grade EEG platforms is, bar relatively few studies, largely anecdotal, and would make an interesting area of investigation, especially with regards to SSVEP control for BCMI. The experiment outlined in chapter 5 of this thesis addresses this issue and compares the accuracy of SSVEP control with a specific focus on BCMI applications.

Flex demonstrates a novel way of exploiting one-to-many mapping through randomising the way in which they are presented to the user. Creating a game-like process presents a different approach to the more direct mappings previously on offer in SSVEP BCMIs. This method is also useful for stochastic music that can enhance both user and audience listening experiences through the introduction of unpredictable variances that in turn influence control choices. Control of *Flex* was designed to be a difficult task, and because of

this as the user I spent considerable time practicing the piece. Aside from the use of arbitrary symbols and the specific mapping strategy used for the piece the *Flex* BCMI could be used in a simpler manner for first time users. In this situation no training or practice would be required other than the calibration necessary for SSVEP classification.

Moving forward, to make musical control more robust accuracy with the SSVEP technique in a portable BCMI requires improvement. This is addressed with the design and build of a new SSVEP stimuli unit, presented in 5. Furthermore the Emotiv device is replaced with a new, lightweight EEG system that can interface successfully with a laptop PC (whereas the signal quality is improved considerably, the cost of this new platform is significantly greater). Whereas systems such as the Emotiv are useful for approximating brain waves, they are not quite ready for providing the levels of accuracy useful for fully exploiting active control. *Flex* is a novel demonstration of how a BCMI can be used to manipulate and control electronic music, and as such can be considered a useful continuation of the previous BCMI systems discussed in chapter 3, where electronic music has been the focus of control.

Again, limitations with regards to performing with a BCMI are still prevalent. Used in this way BCMI is still not particularly engaging for some audience members; the *Flex* BCMI is a particularly exclusive interface with regards to sharing the mechanisms of the interface, hence the amplification of facial expressions. From a user perspective controlling *Flex* is an extremely insular process and from the view of an audience not familiar with experimental music technology the novelty of the system can wear off rather quickly when they are faced with a performer sitting still, conducting no physical gestures and with no visual stimuli other than monitoring facial expressions.

4.6 Summary

This chapter began by outlining some initial factors to be taken into account when designing a new accessible BCMI; portability, EEG measuring hardware and open-source software tools. To understand the practical principles of the SSVEP technique of brainwave control a summary of the major elements, including references to previous studies, is presented in the beginning of this chapter. Accuracy in brainwave control using the SSVEP method is also defined, in particular with regards to music control. This section discusses the stimuli hardware, feedback, colours and patterns and the EEG processing methods required for successful SSVEP implementation.

In order to begin designing and implementing BCMIs for creative applications an initial, a functional BCMI system has been developed for control over electronic music in a live performance setting. The *Flex* BCMI is low-cost system using open-source software with the Emotiv headset that provides a portable platform that is suitable for transportation to music performance venues.

This BCMI system demonstrates a stable GUI combining four SSVEP stimuli and real-time EEG feedback, that uses checkerboard patterns to help alleviate issues rendering flickering patterns on computer monitors. Software has been developed that runs the signal processing, SSVEP classification, transformation algorithms and the surround-sound music performance processing engine for *Flex.*

Flex demonstrates a novel method of turning SSVEP control into a musical game, that takes into account false positive values to produce interesting musical results. It shows how a four-channel SSVEP system can be used successfully for electronic music performance with some generative features and for surround-sound diffusion, where control is limited to only four channels.

The next chapter presents an improved SSVEP BCMI expanded for multiple users. The BCMI system is extended to include acoustic instruments, whose music is controlled by SSVEP based decisions.

Chapter 5: Evaluating SSVEP accuracy and response time with different hardware and creating a multi-user SSVEP BCMI

This chapter presents research that aims to improve aspects of the SSVEP BCMI presented in chapter 4. It is presented in three sections, with each section outlining a particular area of BCMI improvement.

The first section of the chapter outlines an experiment conducted to investigate the accuracy of SSVEP responses from this a new SSVEP stimuli across a group of 11 subjects. The results show an above average level of accuracy available with the new hardware stimuli unit, up to 96.36% during experimentation, and a mean response time of 3.88 seconds with SSVEP detected over a single electrode channel.

The second section of this chapter presents a technical report on the new SSVEP stimuli unit, an open-source, customisable hardware device.

The third section presents Activating Memory, *the outcome of a body of work undertaken in collaboration with the composer Eduardo Miranda. The piece demonstrates how the results from the experiment inform the design of a new BCMI, one that can be used for contemporary acoustic music performance. A new approach to mapping user intention to music is demonstrated through the piece Activating Memory. Here, four BCMI users form a multi-user BCMI system, expanded to also incorporate four musicians. Each BCMI user generates SSVEP selections via one external SSVEP stimulus unit. In total four external SSVEP stimuli units are required for control over four separate musical scores, which are performed by a string quartet to create the overall arrangement.*

5.1 SSVEP Experiment

5.1.1 Introduction and hypothesis

To briefly recap, *Flex* from chapter 4 highlights the issue of control accuracy with a portable BCMI, and measures providing flexible mappings to factor this in were needed in order to take this into account. To improve the accuracy in a portable SSVEP BCMI a new stimulus device is proposed, that separates the graphics rendering needed for icon flickering from the same PC that handles EEG processing and houses the musical engine. The performance and capabilities of the device, along with EEG measuring equipment, helps inform the designs of later SSVEP BCMIs, in particular the piece *Activating Memory*.

An experiment that investigated two key performance features related to the SSVEP stimuli unit, response time and accuracy (defined earlier in section 4.2.1), was conducted. The experiment measures response times and accuracy across eight frequencies. The study aims to investigate whether optimal SSVEP control frequencies exist across a group of subjects, for these two features. It was observed during preliminary tests and early music performances that used prototype versions of the SSVEP stimuli units, that in comparison with the reversing checkerboard icons presented on a computer screen, as used in the *Flex* BCMI, the units provided improvement in both areas. Based on this observation, a user study was designed and carried out to validate this hypothesis.

It was expected that the signal quality of the g.tec platforms would be greater than the Emotiv platform, and that the results would reflect this with better performance across both features. The Emotiv is marketed to the gaming community, whereas the g.tec platforms are targeted towards the fields of medical and BCI research. This is also reflected in the prices of the platforms. The g.tec EEG platforms (which include brain cap, electrodes, amplifier and digitiser) cost approximately £8,000 (at the time of writing),

whereas the standalone Emotiv device costs only £515. Little scientific research has been previously conducted using the Emotiv device, and the algorithms within their proprietary classifiers are closed for evaluation (there are no Emotiv tools for SSVEP detection). One user study has suggested that SSVEP is achievable with the Emotiv (Liu, Jiang et al. 2012), and another indicates the successful detection of the P300 spike (Duvinage, Castermans et al. 2013). However, these studies are isolated and further evaluations are necessary to, especially as many in the BCI community are sceptical of such devices and steer clear of them. That said, if SSVEP control using the Emotiv is quantifiable beyond the anecdotal observations of control with the *Flex* BCMI (which are not conclusive), then the device could be of interest to those working in the arts or music therapy for active control. Especially as it is accessibly priced and the demands of a more artistic setting do not always require the same level of accuracy that BCI control in a medical or research-orientated application require.

An experiment was designed to determine a baseline average of the two features, response time and accuracy, across a group of eleven subjects. Two subjects general had prior exposure to SSVEP icon gazing for BCMI. The imbalance was to explore how the SSVEP BCMI could perform in scenarios where users have no previous experience and minimal training, such as in hospitals where BCMI systems for patients need to be quick and easy to setup and use. Including two experienced users allowed for some general observations on the effects of previous SSVEP control. One of the primary aims of the experiment was to contribute knowledge towards BCMI design for use in uncontrolled environments for first time users, with a minimal approach – in terms of electrode channels used for detecting SSVEP, for a short setup time. The experiment consisted of two tests. Test 1 recorded the response time across eight frequencies. This is useful for standard four-channel SSVEP control as it can identify frequencies that offer the fastest response. Another reason for testing against eight frequencies was that the four-channel

units were designed to be modular, with the potential of future SSVEP BCMIs combining more than one unit. The results are measured over all eight channels, but also take into account the four best performing frequencies per individual.

5.1.2 Related work

A similar study investigated the performance of the Emotiv headset against the medical-grade ANT[16] EEG device using the P300 method (Duvinage, Castermans et al. 2013). Results implied that the Emotiv headset produces lower accuracy when detecting event-related potentials than more expensive medical EEG devices. A survey of BCI methods for computer gaming with the Emotiv indicated that users and researchers preferred active BCI methods even though control was often seen as limited due to the number of options available (Ahn, Lee et al. 2014), however this would be an interesting survey to undertake with regards to music-making.

A number of other studies investigating SSVEP accuracy and response time have been conducted in the past, using a range of hardware and software platforms, electrode channel combinations and signal processing techniques. A selected few, representing specific points of relevance and interest are discussed here. Friman, Volosyak et al. (2007) present results from testing various methods of on-line SSVEP classification. Mean values of accuracy across subjects ranged from 59% (taking average values across electrodes) to 84% accuracy across 6 choices with 10 subjects, where 84% was measured using a technique called minimum energy classification (Friman, Volosyak et al. 2007). The study used 6 passive electrodes, requiring the application of conductive paste. Another study, by Lee, Yeh et al. (2011), analysed user responses across flickering frequencies with different duty-cycles. Here, they measured both response time and accuracy across 6 subjects.

[16] https://www.ant-neuro.com/

Optimum settings for best performance across both of these parameters was an LED stimuli with a flickering frequency of 13.1Hz detecting SSVEP across one bipolar channel (electrode position as Oz as the main signal channel), using a high duty cycle of 89.5%. Using a threshold classifier, in similar manner as applied in the experiment outlined here, they reported a mean accuracy of 82.08%.

Interestingly, in relation to the *Flex* BCMI stimuli, a study by Wang, Wang et al. (2010) measuring SSVEP accuracy and response time using pattern reversal on a CRT monitor yielded particularly high results. Here, mean accuracy across 16 choices was 97.2% with a response time of 3.08 seconds. Although the results were very promising the study was only conducted across three participants and used eight electrodes across the visual cortex area (as opposed to the minimal number of electrode channel used here). A study of a similarly minimal approach to SSVEP detection (one electrode channel, real-time analysis) compared different approaches to classifying signals with varying results. Although accuracy across trials was lower here (51% - 67%), response times were significantly higher, with positive SSVEP detected at mean times of approximately 1.6 seconds (Wilson and Palaniappan 2009).

Of significant relevance to this research is an experiment conducted by Guger, Edlinger et al. (2011) who tested an on-line SSVEP classifier using similar g.tec hardware and software. (Although not exactly like-for-like), to the equipment used in the experiment here. Their study used a high volume of trials across three users resulting in a mean accuracy of 82.7%. An important distinction between their experiment and others mentioned here is that their BCI uses an LDA (Linear Discriminant Analysis) classifier, a machine learning technique, which requires subjects to undertake a training exercise prior to use. This approach, combined with the use of 9 electrode channels for analysis may be the reason for the fast response times they report, with a mean value of 0.25 seconds. Finally, to date, only one major study surrounding the feasibility of using SSVEP with the

Emotiv has been conducted, by Liu, Jiang et al. (2012). Their results indicate a much higher level of accuracy than was achievable in this experiment, with their on-line test results showing a mean accuracy of 95.83±3.59%, a level on par with the g.tec platform they tested against. The mean response time they recorded was 5.25±2.14 seconds, which is closer to the findings of this experiment. However, their test used extra electrodes at the edges of the occipital area (P_7 and P_8 in addition to O_1 and O_2) to help determine SSVEP, as well a trained classifier.

5.1.3 Methods

This section discusses the participants, experimental procedure, the hardware platforms and specific technical considerations.

5.1.3.1 Participants and experimental procedure

11 participants from the ICCMR research group volunteered to be the subjects of the experiment. Across the subjects was a gender ratio of 10 male to 1 female, all with normal or corrected-to-normal vision. Subjects fell between 3 age ranges, 20 – 30 (6 participants), 30 – 40 (3 participants), and 40 – 55 (2 participants). Three subjects had previous experience using SSVEP BCI control but only one subject had previous experience using the external SSVEP LED stimulus units. Participants were screened for a history of epilepsy and provided written consent regarding use of their data (Appendix 2). None were found to be at risk of epileptic seizure (low frequency flashing, at rates within the stimuli unit's range, are known to induce fits in a small proportion of epilepsy sufferers (Fisher, Harding et al. 2005)). The experiment was conducted inline with ethical approval granted by Plymouth University (Appendix 2).

Such BCI studies pose particular problems, most notably due to the unpredictability of individual user abilities with regards to controlling measured EEG patterns. The terms

‘BCI illiterate’, ‘inefficiency’ and ‘weak’ have been used in the past to describe those who are unable to generate brainwave patterns consistent with the majority of people (Kübler and Müller 2007). As such, previous BCI experiments have been conducted across a range of user abilities that can present difficulties when comparing results. For example, McFarland, Sarnacki et al. (2010) conducted a ground breaking BCI experiment testing detected motor imagery (a form of imagined control) across three simultaneous dimensions. The authors note however, that subjects were from a pool of the best performing subjects in previous tests, and were all selected through a pre-test screening. This puts into question the reliability of their method across subjects chosen at random. To more effectively validate BCI experiments a wider pool of users seems appropriate, and across a wide a demographic as possible.

All experiments were conducted in an open-plan office filled with electrical computer equipment operated by other researchers during experiments. An electromagnetic field screening fabric was positioned around the participant workstation to reduce interference, but the fabric was not sealed (it was left open on two sides) thus only partially minimising the effects of localised electrical interference. This environment was used to replicate the similar settings of the musical applications of BCMI in this thesis, such as concert venues. Therefore if suitable results can be measured in an open plan office with plenty of electrical equipment, then it is highly likely that the system will work elsewhere.

The experiment, which consists of two tasks, was repeated three times across three different EEG measuring platforms. Subjects were provided with a two-minute break between each task to allow a period for resting their eyes, in between gazing at the flickering stimuli. Additional breaks were available upon request at any time during the experiment for this purpose.

5.1.3.2 Experiment equipment

To recap, the different EEG measuring platforms are:

- **Platform 1.** g.tec g.Sahara active (dry) electrodes system.
- **Platform 2.** g.tec g.Gamma passive (wet) electrode system.
- **Platform 3**. Emotiv epoc EEG headset.

It is useful to compare the effects of wet electrodes with those of dry electrodes as there are benefits and drawbacks of both to those interested in musical EEG applications. Passive electrodes require a liquid, gel or paste application, to reduce the impedance. This leaves a lasting stickiness (albeit temporary), increases the time taken to setup, and requires washing of equipment and hair. The g.Gamma electrodes were applied with conductive gel after some abrasive paste was applied to the skin at the electrode positions, as per the manufacturer's instructions. The Emotiv electrode pads were applied with saline solution prior to each use. Active electrodes, which contain an amplifier inside, require no gel application and are therefore more straightforward and quicker to setup. The active g.tec Sahara electrodes each house 8 pins designed to access skin through hair to help reduce impedance. The benefit of passive electrodes is a more robust signal against the improvement of user experience (i.e. no gel in hair) with active electrodes. Dry electrodes are particularly useful for preparing BCMI users quickly as electrodes can be secured in a brain-cap before it is put on. The downside to this is that dry electrodes are more prone to noise, especially away from controlled laboratory conditions. Due to this increase in interference the extra distance between the signal and reference electrodes provides a wider reference area albeit with a potential increase in the overall signal-to-noise ratio. This issue also contributed to the motivation behind the design of the external SSVEP stimulus units.

SSVEP control was extracted using the band power extraction method outlined in section 3.2.1. Data recording was synchronised to the flickering control of the external SSVEP stimulus units so that response times could be recorded from the start of LED flickering. Data was both written to a comma-separated values (CSV) file for offline analysis and presented as a graphical chart for calibration in real-time.

The SSVEP stimuli units were controlled via a USB serial connection that allowed for synchronisation to record EEG data during flickering. Stimuli frequencies were chosen from the high theta (theta waves ≈ 4 – 7Hz) and alpha (≈ 8 – 13Hz) ranges, as outlined in section 3.2.2.1, and with a duty cycle of 50:50. For part 1 of the experiment the unit's TFT screens were turned off so as not to distract subjects, whereas during part 2 each screen displayed a number corresponding to the four options available during the experiment.

5.1.4 Main experiment

The experiment was conducted in two parts, the first to test response time and the second to measure accuracy across a series of trials. Both parts of the experiment were repeated for each participant across all three platforms.

- **Test 1.** Prior to data collection subjects are connected with the EEG headset and asked to relax for a period of one minute. An average baseline amplitude response is recorded for comparison against positive SSVEP detection.

  Subjects were asked to focus their gaze at the top left LED array whilst the LEDs were off. Upon receiving a command from the host laptop the LED array flicker for 15 seconds at the first frequency. A threshold value of approximately 1/3 of the maximum response value and > 10% above the baseline amplitude is determined and stored for classification. After a 20 second rest period the same flickering frequency is presented, again for 10 seconds. EEG data is recorded from the start of the flickering and a timer, started at the same time, derives the time taken from

the start of the flickering until the subject's response has increased above the threshold recorded in the previous trial. This one-trial, one-test approach is repeated across the 8 frequencies in total, 7Hz, 7.5Hz, 8Hz, 9Hz, 10Hz, 11Hz, 12Hz, and 12.5Hz.

- **Test 2.** The second part of the experiment was conducted to determine the accuracy of the SSVEP responses when subjects were presented with multiple choices. Where the first part of the experiment is useful for determining speed of SSVEP response, and therefore speed of control in application, it is not useful for determining whether flickering stimuli can cause false positive values across other frequencies nearby as only one icon is presented at a time.

  Subject threshold values taken during the first trials of test 1 were used again for test 2 (again to test the response of the system against minimal calibration). Four flickering frequencies were presented on the four LED arrays of the unit for a maximum of 15 seconds. The four frequencies, 7Hz, 8Hz, 10Hz and 12Hz, from the high theta and alpha ranges, were chosen as a representative spread across the frequencies used in test 1 to observe any differences across the range. Across 10 trials subjects were asked to select any one of the four images on the TFT screens by gazing at the corresponding flickering LED array. The system recorded the detected channel (or if there was no detection) and this was corroborated against subjects' self-report. A final value of true or false was recorded for each trial, confirming a successful or failed detection of user choice.

5.1.5 Results: Test 1

This section presents the results of test 1 firstly across all 8 stimulus frequency channels and then across the best performing four.

5.1.5.1 Results across 8 stimulus frequencies

Across all 264 trials in test 1 (8 trials per platform, per user), not counting the calibration trials, there were 5 trials where no positive SSVEP response was detected, and these were all recorded with the Emotiv headset. Results from these trials are excluded from the data presented below.

Table 7 presents the mean times across all 8 frequencies and each platform, for each subject. The data from this table is visualised in Figure 19. Although mean response times vary across individuals and platforms standard deviation (σ) is acceptable ($\sigma <= 0.05$) across all subjects.

User	EEG platform	Mean time (secs)	Std. deviation (σ)
1	g.tec dry	5.44	0.03
	g.tec wet	6.92	0.03
	Emotiv	9.44	0.04
2	g.tec dry	5.54	0.02
	g.tec wet	6.31	0.02
	Emotiv	7.86	0.04
3	g.tec dry	5.62	0.03
	g.tec wet	7.52	0.04
	Emotiv	10.54	0.05
4	g.tec dry	4.89	0.02
	g.tec wet	7.42	0.04
	Emotiv	8.29	0.04
5	g.tec dry	5.91	0.03
	g.tec wet	7.50	0.03
	Emotiv	9.60	0.05
6	g.tec dry	7.15	0.03
	g.tec wet	6.44	0.02
	Emotiv	8.17	0.04
7	g.tec dry	7.90	0.05
	g.tec wet	6.23	0.02
	Emotiv	7.75	0.04
8	g.tec dry	8.87	0.04
	g.tec wet	8.15	0.03
	Emotiv	10.77	0.04
9	g.tec dry	4.29	0.02
	g.tec wet	7.43	0.04
	Emotiv	6.88	0.02
10	g.tec dry	7.11	0.04
	g.tec wet	8.60	0.03
	Emotiv	8.89	0.04
11	g.tec dry	3.18	0.01
	g.tec wet	5.04	0.01
	Emotiv	6.91	0.01

Table 7. Mean response times and standard deviations to two decimal places for all subjects for each platform across all stimuli frequencies.

Paired t-test analysis (see table 8) shows the statistical significance of the response times across the three platforms using three paired t-tests. If a null hypothesis is that there is no significant difference between the results of the platforms, the p values contradict this and suggest that the results are statistically significant as they are under the threshold of sufficient significance (5% or a *p* value of 0.05), except the *p* value of platform 2 vs 3, which is slightly over. This value is likely to be reduced by the inclusion of more participants in the study, which would provide a larger data set.

t-test	***p* value**
1 vs 2	0.0239
1 vs 3	0.0003
2 vs 3	0.0507

Table 8. Three paired student t-tests determine the statistical significance of all user response times from test 1.

Results indicate that the g.tec dry electrodes produce the fastest response times from all three platforms. This presents an interesting finding, especially in comparison with the g.tec wet electrodes. The only variable that differs between the two platforms (aside from the electrodes themselves) is the electrode amplifier; g.Gamma for the wet electrodes and g.Sahara for the dry. It can therefore be assumed that the difference in amplifier may contribute to this. To examine the difference in response times across low and high frequency bands table 9 presents the mean response times and standard deviations for all users. Table 9 suggests that across both frequency bands (and across the full bandwidth) platform 1 produces faster response times than platform 2, which produces faster responses than platform 3. Figure 19 illustrates this further by plotting the mean response of all users for each platform against all 8 frequencies.

Frequency band	EEG platform	Mean time (secs)	Std. deviation (σ)
Full range	1: Dry	5.99	0.03
	2: Wet	7.05	0.03
	3: Emotiv	8.64	0.04
7.5 - 9Hz	1: Dry	5.17	0.03
	2: Wet	6.53	0.03
	3: Emotiv	8.39	0.04
10 - 12.5Hz	1: Dry	6.93	0.04
	2: Wet	7.44	0.03
	3: Emotiv	8.82	0.04

Table 9. Mean response times and standard deviation across all subjects, for full, low and high frequency bands.

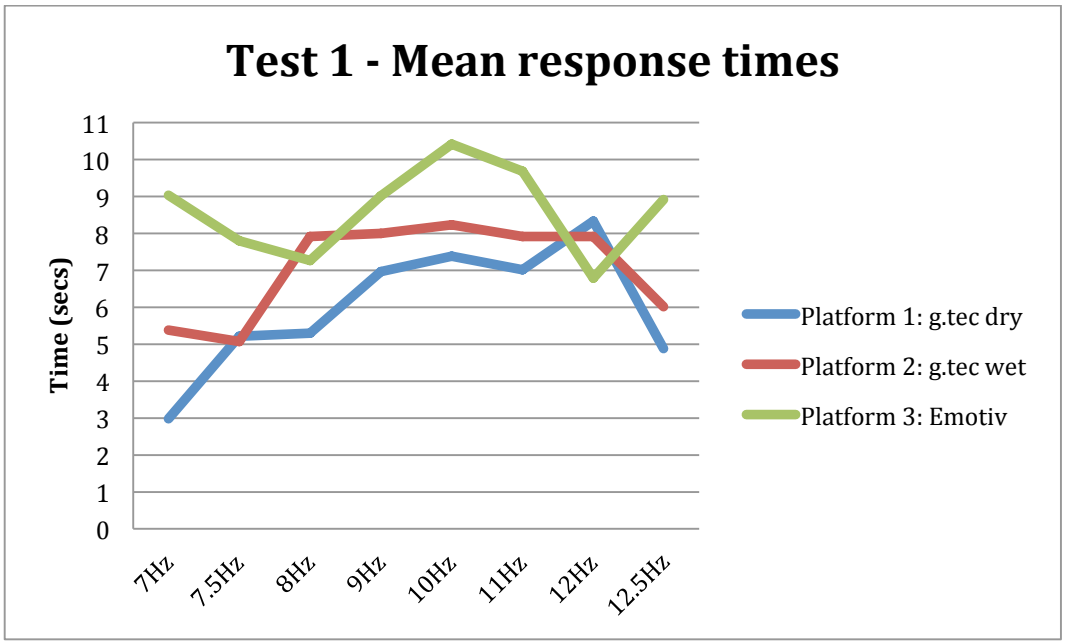

Figure 19. Mean response times across all subjects over the three platforms tested.

Figure 19 also illustrates how wet and dry g.tec electrodes produced faster response times at lower frequencies, and also at 12.5Hz. This is also apparent when observing mean response times for all 11 subjects across low (7 – 9Hz), high (10 – 12.5Hz) and full range (7 – 12.5Hz) frequency bands for each platform (Figures 20 – 22).

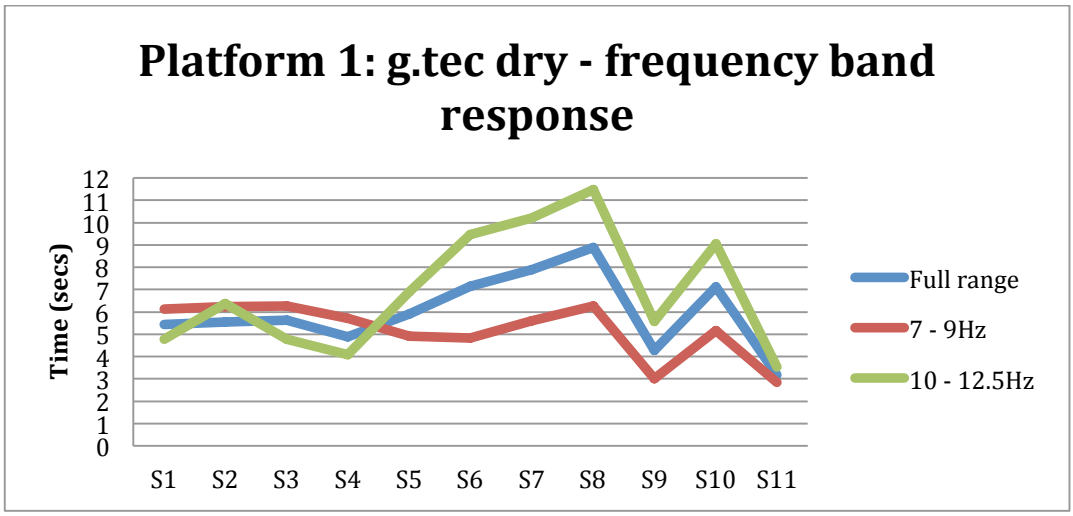

Figure 20. Mean response times using platform 1, g.tec dry electrodes, for each subject across low (7-9Hz), high (10-12Hz) and full range frequency bands.

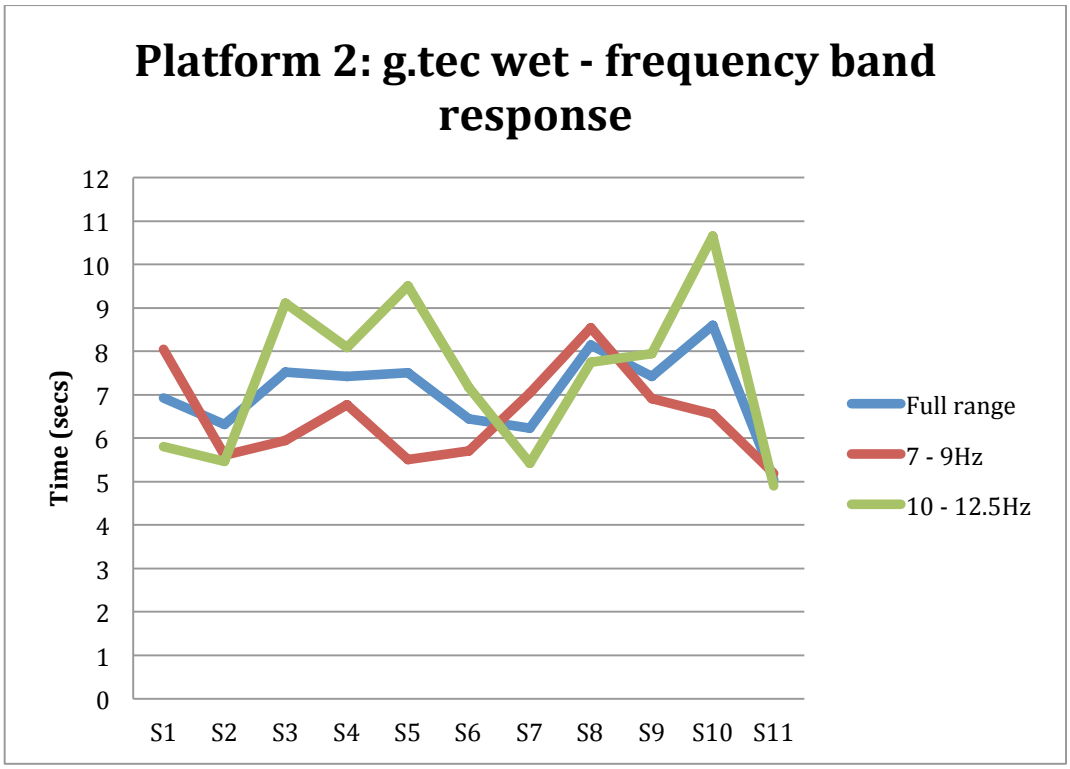

Figure 21. Mean response times using platform 2, g.tec wet electrodes, for each subject across low (7-9Hz), high (10-12Hz) and full range frequency bands.

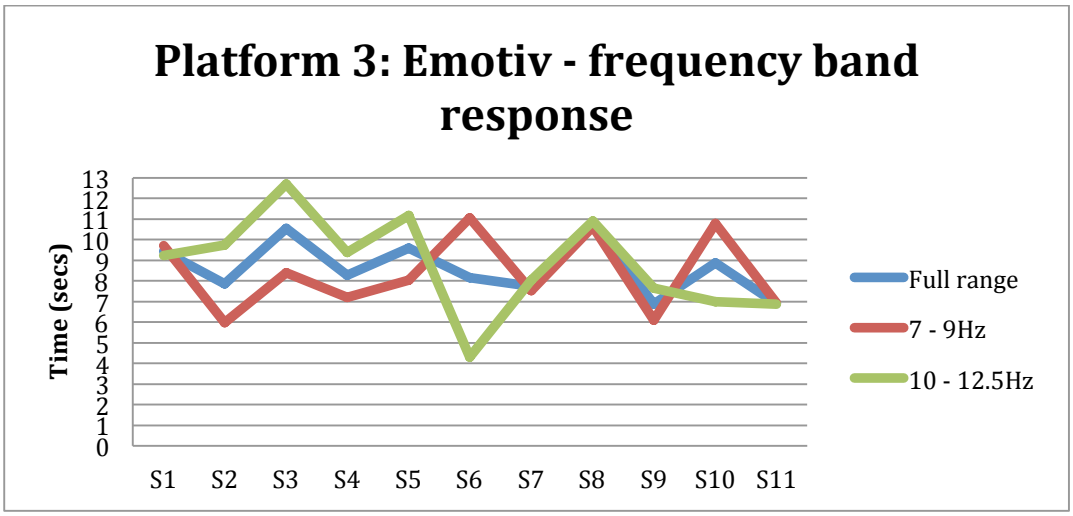

Figure 22. Mean response times using platform 3, the Emotiv device, for each subject across low (7-9Hz), high (10-12Hz) and full range frequency bands.

5.1.5.2 Results across four best performing stimuli frequencies

A BCMI that can facilitate selecting the four stimulation frequencies that elicit the fastest response would be particularly useful. The data from the frequencies that elicited the fastest four responses for each user, across the same platform, provides an interesting perspective for implementing a 4-channel SSVEP interface using frequencies selecting the best frequencies for each user (see Table 10, Figure 23). From this perspective mean response times are much faster and standard deviation, measured across each user's ranges, is considerably lower than when measured across all 8 frequencies.

Subject	Mean time across 4 freq. (secs)	Platform	Min	Max	Std. deviation (σ)
1	2.43	1: Dry	2.01	2.76	0.00
2	4.01	1: Dry	3.33	4.66	0.01
3	4.74	2; Wet	2.19	7.42	0.02
4	3.50	1: Dry	1.50	4.83	0.01
5	3.79	1: Dry	2.99	4.70	0.01
6	5.14	2: Wet	4.70	5.64	0.00
7	4.11	1: Dry	2.10	4.89	0.01
8	5.70	1: Dry	3.34	7.50	0.02
9	2.78	1: Dry	2.22	4.11	0.01
10	4.15	1: Dry	3.61	5.43	0.01
11	2.30	1: Dry	1.64	2.99	0.01

Table 10. Mean response times, standard deviation, minimum and maximum response times, across the four best performing stimuli frequencies for each subject, for all platforms.

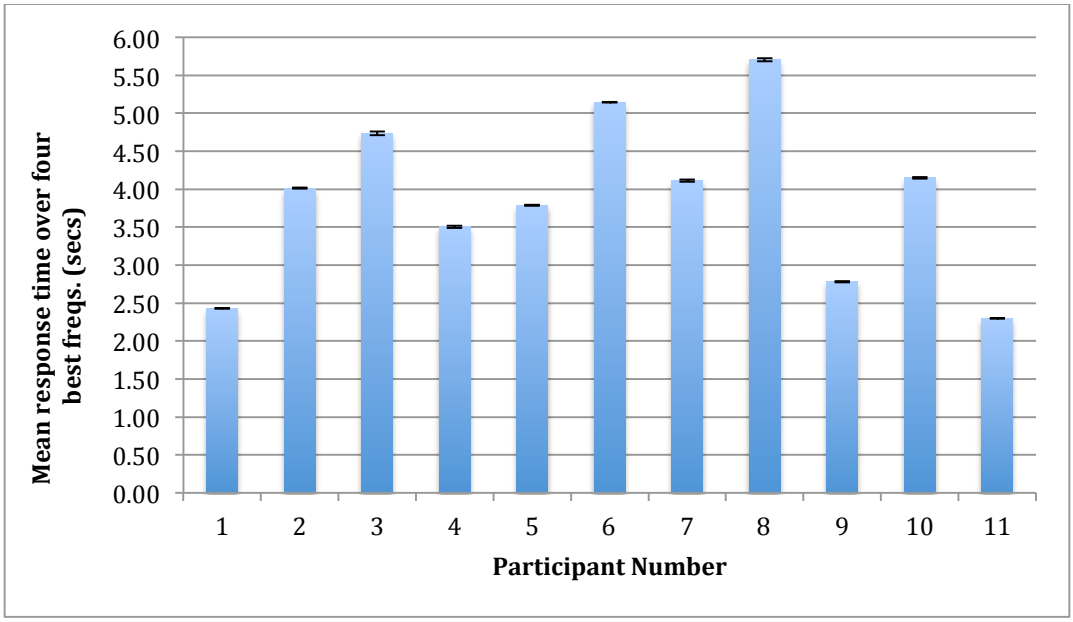

Figure 23. Mean response times across four best stimulation frequencies with standard deviation shown in error bars, across all participants.

The mean response time across all users' fastest four response times is **3.88** seconds (see Table 11), which is an acceptable response time considering the limitations imposed on the experiment. In cases where subjects had previous experience to SSVEP control the mean time is as low as 2.30 seconds, with a minimum response time of 1.64 seconds

(subject 11). Even subjects without prior experience were able to record very fast response times down to 1.50 seconds (subject 4) (see Table 10).

Mean (secs)	Std. deviation (σ)	Std. error of mean	Variance
3.88	0.01	0.31	1.07

Table 11. Overall mean response time, standard deviation, standard error of mean and variance across all subjects.

With regards to identifying the frequencies that elicited the fastest response times across all subjects Figure 24 highlights the amount of times each stimuli frequency featured in the subjects' best four frequencies (with a maximum of 11 times possible). Interestingly, 7Hz followed by 12.5Hz then 7.5Hz feature as the three most common frequencies in this list. Therefore they can be considered as the three most consistently fast stimuli frequencies for this group of subjects. Overall, 7Hz produced the fastest response times across all subjects with a mean time of 3.282 seconds (as an average of the trials considered for best four), followed by 8Hz then 10Hz. 9 subjects recorded their four fastest responses using platform 1, 2 using platform 2 and none using platform 3.

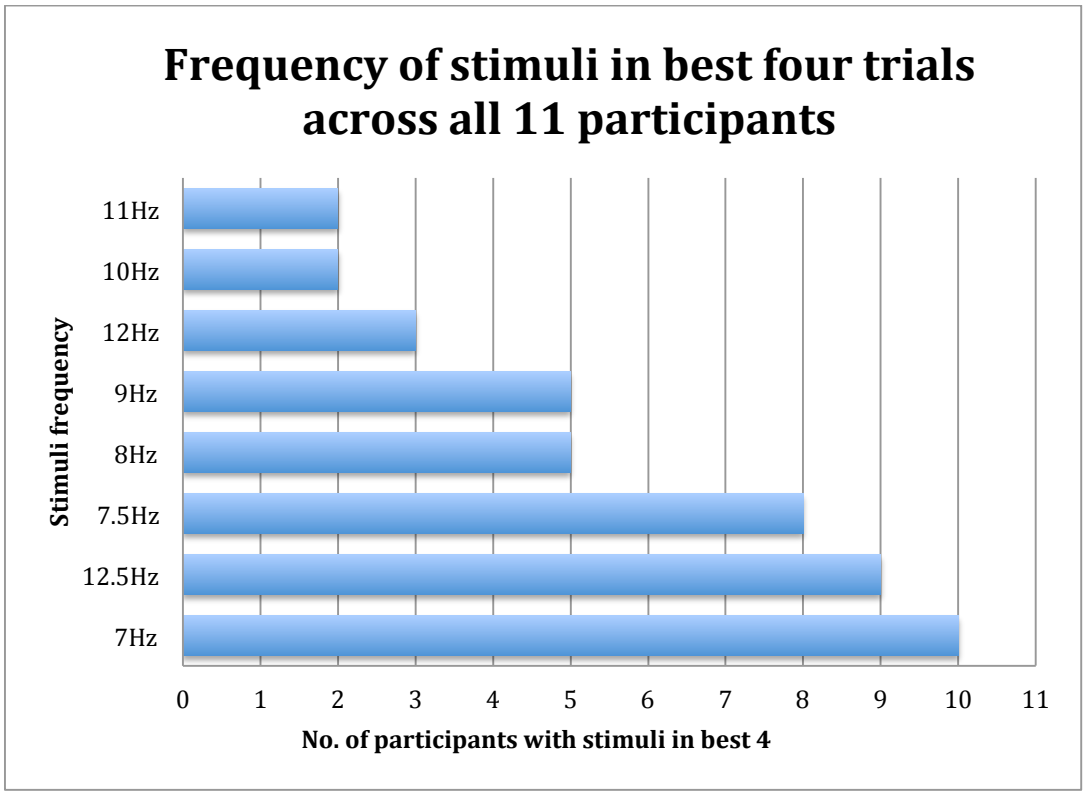

Figure 24. Amount of times of stimuli frequencies appear in best four performing stimuli across all users. The 7Hz stimulus is in the top four for 11 users, whereas 11Hz and 10Hz appear only once.

5.1.6 Results: Test 2

Figure 25 illustrates the accuracy recorded over 10 trials for each platform and for each participant. Accuracy is measured as the system's successful detection of user selection over 4 choices. Overall, for both platforms 1 and 2 accuracy for all individual subjects is >=70%, with only 16 false detections from a total of 220 choices (10 trials x 11 subjects x 2 iterations (one for each platform)). Platform 2 detected the most correct user selections at an average rate of 96.36%. The Emotiv headset, platform 3, had the lowest measure of accuracy at 60% across all 11 subjects, however this is still above the 25% baseline of random detection, whereas platform 1 recorded 90.91% accuracy and platform 2 recorded 96.36% (see Table 12).

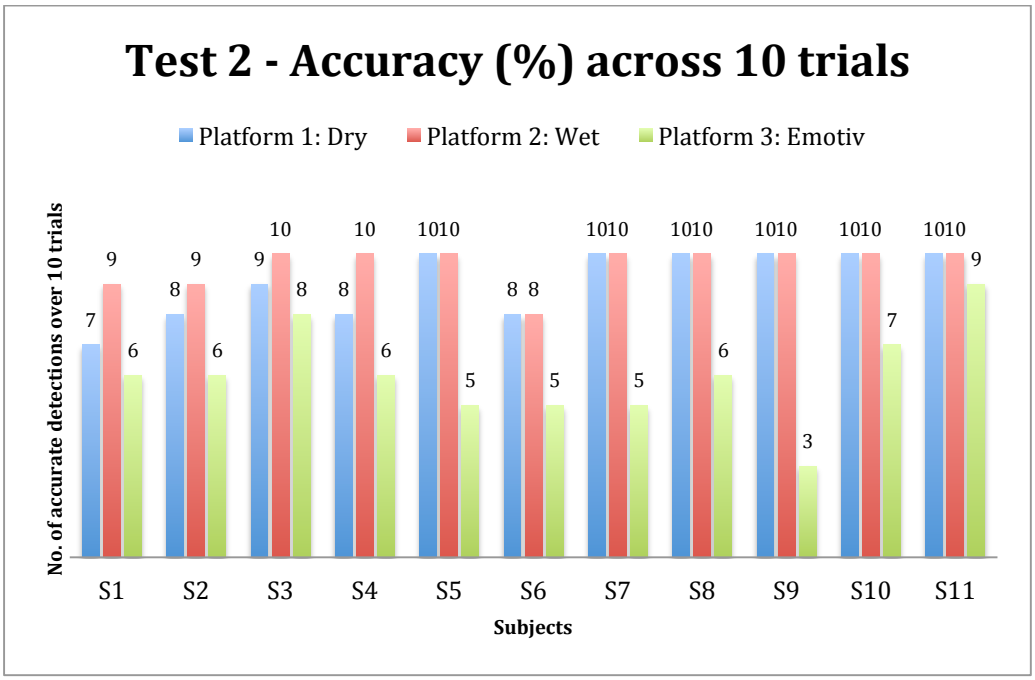

Figure 25. Accuracy of selection task across 10 trials across all three platforms for all subjects.

Platform	Mean accuracy (%)	Std deviation (σ)
1. Dry	90.91	0.01
2. Wet	96.36	0.01
3. Emotiv	60.00	0.02

Table 12. Mean accuracy and standard deviation of all three platforms across all subjects.

5.1.7 Discussion and observations

The results from test 1 show that in all but six instances across eighty-eight trials a positive SSVEP response was detected across all subjects in the corresponding frequency bands. The mean response times across all eight stimuli frequencies are notably slow, especially in comparison with the previous studies mentioned in section 4.3.1. For BCMIs with more than 4 channels of control more investigation into frequencies both in between the frequencies used and beyond the upper and lower boundaries may be appropriate. Additionally, a smaller sampling window for band power extraction would yield faster data, with a potential trade-off in accuracy. For a 4-channel BCMI selecting the stimuli

frequencies that elicit the best response is a useful approach in BCMI design as it takes into account individual preferences.

Looking at the mean times from the four best performing frequencies per subject shows that both response times are more consistent with each other (standard deviation is much lower) and that across four stimuli all users can affect control in less than 6 seconds, with a mean response time across all subjects of 3.88 seconds. This is not too much slower than the mean response time reported by Wang, Wang et al. (2010), although their BCI employed 8 electrodes across the visual cortex as opposed to the 1 used here. There is a distinct correlation between experience and response time as seen by subjects 9 and 11, both with previous SSVEP control experience. Subjects 1, 9 and 11 all have a mean response time of less than 3 seconds and subjects 4 and 11 have minimum response times of 1.5 seconds and 1.64 seconds respectively.

Of the stimuli frequencies used 7Hz produced the fastest response times across all subjects (see Figure 24). One explanation could be due to the stimuli always being presented first during task 1 and responses may deteriorate as exposure to the flashing lights progresses. However, this does not explain how 12.5Hz, which was the last stimuli presented during task 1, elicited the second fastest response times. In my own practice outside of the experiment 7Hz continues to elicit the fastest, and strongest response. This was also observed during productions of *Activating Memory*, where a number of users with no previous BCI experience elicited the strongest control over this frequency.

With regards to platform 3, response times from test 1 indicate that positive SSVEP response can be successfully detected, but this should be considered alongside the levels of accuracy recorded in test 2, which is poor – in nearly all incorrect recordings the system detected a positive SSVEP measure in an opposing channel. With this in mind it seems likely that false positive values, which contributed to incorrect detections in test 2,

account for at least some of the data in test 1, therefore in a practical context where multiple SSVEP channels are presented simultaneously the results from test 2 may have negative implications on the results from test 1.

The results from test 2 show that platforms 1 and 2 offer very high accuracy (90.91% and 96.31% respectively), both in comparison with platform 3 (60%) and against the previous studies mentioned in section 4.3.1. In the BCI research field the threshold of accuracy if often cited as 70% to achieve useful communication (Hammer, Halder et al. 2012), and the results from platforms 1 and 2 far exceed this. One contributing factor to this level could be the brightness and size of the LED arrays. There are 40 LEDs within each array which, when combined, emit a very strong and bright flashing light. No previous studies of SSVEP stimulation have reported using such a large component for stimuli, and this brightness and size may contribute to such a strong response. Subjects reported that they found it easy to lock-in their gaze on an array, although as reported by experienced users, use can become tiring much sooner when using LED stimuli over those presented on a computer screen.

Platform 2, with the g.Gamma wet electrodes, offered the highest level of accuracy from the three platforms during test 2. This is to be expected due to the wet electrodes inherently picking up less localised noise thus delivering a more stable signal with reduced false positive values. Again, wet electrodes are known for their stability, and coupled with conductive gel applied between the electrode and the scalp provides a more robust signal path.

A few further observations from the experiment are worthy of some discussion. As already mentioned the two subjects (9 and 11) with previous experience demonstrated faster response times and accuracy. Interestingly, this improvement against other users is only apparent across platforms 1 and 2. This suggests two things. Firstly, that it seems highly

probable that with further experience other subjects may be able to improve on their response times and accuracy, and perhaps even the two subjects with experience may be able to improve their results further with more training. Secondly, the results from the experienced users contribute to the difference in consistency between the first two platforms and platform 3.

Feedback, visual or otherwise, was omitted from the experiment. The decision to remove feedback was made in order to test the SSVEP unit in its most basic state. Real-time feedback can help assist subjects in learning how to correctly focus their gaze during selections and teach them how to generate stronger responses. Therefore it can be assumed that there could be some improvement in the data with feedback implemented. The TFT screens only displayed numbers (1 – 4 to indicate the available choice), no music was generated as a result of SSVEP control and as such users were not learning as they progressed throughout the tests. This allowed for every stimulus frequency across all three platforms to be tested without bias and with minimal user training.

There are two factors that heavily influence response time, the a^{min} threshold value, which is set on the fly, and the window size of the band-power extraction in the EEG processing. Increasing the number of calibration trials from 1 is highly likely to result in attaining a more accurate threshold value, which may be lower than the one that set and subsequently shorten response time. Also, by shortening the window of the band-power calculation may also increase as shorter windows are approximated. However, it is also possible that this second factor may reduce the accuracy of the system as noise will be amplified further when increasing the resolution in this way.

5.1.8 Conclusions

Results from the experiment strongly indicate that without any user training and a one-stage calibration trial per channel SSVEP response can be successfully detected in EEG via

the external flashing stimuli unit. The results of the two tests indicate that the SSVEP method used and stimuli units provide a high level of accuracy and a reasonable response time suitable for real-time music control.

In comparison with the experiments presented above in section 4.3.1, the results appear to be consistent with other systems, and in certain cases can be viewed as an improvement. A mean accuracy rating of 96.36% for platform 2 exceeds that of other studies (Friman, Volosyak et al. 2007, Guger, Edlinger et al. 2011, Lee, Yeh et al. 2011, Liu, Jiang et al. 2012) as well as the 70% threshold commonly accepted in BCI research, although response time is a little slower. For BCMIs that need to prioritise greater accuracy over response time then platform 2 is the most viable, whereas for a faster response platform 1 is recommended (with ≈6% less accuracy). The results from this study are likely to improve if some recommendations, based on the methods in previous studies, are implemented. These include using additional electrode channels, increasing the duty cycle of stimuli flickering and applying more complex classification algorithms. As mentioned already, increasing the duty cycle has previously been demonstrated to increase amplitude in SSVEP response, but also to improve visual comfort for users (Lee, Yeh et al. 2011). The SSVEP unit allows for manipulation of this parameter by adjusting the ON and OFF times of the flicker cycle through the programmable sketch.

One feature that was not tested in the experiment was investigating a^{max}, and subsequently the range of amplitude control available across the frequencies. For an SSVEP BCMI that wishes to use amplitude control this would be of significant interest, and a future experiment may wish to incorporate this, especially with feedback to help subjects perform amplitude control.

The technique of measuring response across a frequency range and selecting the four best performing frequencies can be applied as a crude but efficient method for quickly

optimising a 4-channel BCMI for individual use. The system used in the experiments can be adapted to remember individualised configurations including best choice flashing frequencies and their associated thresholds, whilst offering on-the-fly fine-tuning of threshold values to optimise performance in different environments over multiple sessions. Furthermore the SSVEP units can be programmed to flicker across a wider frequency range than the one used in the experiment, to tailor the system's response to individual preferences.

5.2 Improving SSVEP accuracy with an open-source, customisable and low-cost stimuli device

5.2.1 Introduction

This section focuses on the design and testing of an external SSVEP stimulus unit. An overview of the LED stimuli method and how it is employed in the units is given, including the components and overall functionality, as well as how the units are employed in the piece *Activating Memory.*

The aims of the SSVEP stimuli units are to provide a stable platform for stimuli presentation and improve upon the SSVEP control on offer in the *Flex* BCMI. To achieve this the SSVEP stimuli is moved away from flickering icons on computer screens towards a dedicated hardware unit that can perform icon flickering, display images, provide user feedback, and integrate with the other components necessary for BCMI performance.

5.2.2 Improving SSVEP response with LEDs

As touched upon in chapter 3 the *Flex* BCMI highlights a need to improve SSVEP accuracy in a portable BCMI. One particular observation during development of *Flex* was the difficulty in generating precise icon flickering on a laptop computer screen. A study conducted by Wu, Lai et al. (2008) found that when using the flickering technique of lights flickering ON and OFF (as opposed to the checkerboard reversal technique), SSVEP response was significantly stronger with LED stimuli rather than CRT or LCD. In light of this finding initial tests were conducted using LEDs that indicated that a stronger (in terms of amplitude) and more consistent SSVEP response could be generated using LED lights. One of the reasons for this is that LEDs can be programmed to flicker via a dedicated microprocessor, separating the BCMI computer processing from the icon

flickering entirely. Wu et al's review of stimuli also highlights that spectral differences between the three mediums of flickering are likely to affect SSVEP response. Their findings suggested that the spectrum of the LED flicker contains only the fundamental frequency and harmonics (integer multiples of the fundamental). Also, the spectrum of the CRT is the most complex with additional refreshing frequency components, and finally the LCD spectrum contains extra low frequency harmonic content that can result in noisy overtones. Therefore the medium of the stimuli can have a strong affect on the SSVEP response, with the extra harmonic and non-harmonic content in CRT and LCD screens contributing to the noise found in SSVEP responses which is likely to result in less accurate control.

In their review of SSVEP stimulation methods Zhu, Bieger et al. (2010) noted the difficulty in ascertaining which colour is best for LED SSVEP stimulation (or any of the other mediums), as up until their review (and seemingly to the present) a dedicated study has not been undertaken that compares user response to different colours. However, the two best performing systems they reviewed both employ green stimuli, whereas red coloured stimuli has been suggested to be perceived as more provocative (Takahashi and Tsukahara 1976, Fisher, Harding et al. 2005). As such the default LED array colour for the units is green, and this was used for the experiment here. Zhu and colleagues also acknowledge that a good solution for practical applications is to design adaptable stimuli that can be configured to each user, depending on their individual response and preferences. The SSVEP units described here adhere to this suggestion, through the full range RGB combinations available with the LED arrays, which can be easily adjusted through re-programming the microcontroller.

In light of their review Zhu, Bieger et al. (2010) suggest four important goals to be achieved when enhancing SSVEP stimuli, and the SSVEP stimuli units addresses each of

them as follows:

1. To maximize selective attention and to minimise eye movements with respect to the controlled element

Selective attention is maximised with the unit through the layout of the LED arrays and TFT screens. A user, when positioned in front of the unit at a distance of 30cm or further, is able to gaze at all four icons and four screens with no movement required (although it becomes more comfortable at upwards of 40 cm distance). Furthermore, with feedback incorporated into the LED arrays the user is informed of SSVEP selection, again without a need to significantly alter their gaze or position.

2. To increase the number of available frequencies

Although each unit offers 4 SSVEP channels, the units are modular and can be multiplied in extend the number of SSVEP channels. This is realised in the two BCMI systems outlined in chapter 6, where two units are combined to deliver 8 channels of simultaneous SSVEP control. Additional channels help extend the music control possibilities within a BCMI, widening the mapping options.

3. To enhance the SSVEP SNR

The results from the experiment this chapter indicate that SSVEP accuracy, combining the appropriate EEG measuring platform with the external SSVEP stimulus units, is particularly high. A useful comparison would have be to judge the results from the units against SSVEP detection using the computer monitor based stimuli in the *Flex* BCMI, but this was beyond the scope of the experiment.

4. To change an SSVEP-based BCI from dependent to independent

Developing SSVEP stimuli that are independent of any physical movement (as muscle

activity is required for gazing) seems an unlikely prospect, although it would be beneficial for those with more extreme physical disabilities. Brainwave control without the use of external stimulus is likely to be more suitable for this, and one method of passive control is explored for use of BCMIs in chapter 6.

5.2.3 Technical report of design and build of SSVEP stimulus device

5.2.3.1 Objectives

The external SSVEP stimulus units are designed to provide a customisable platform for developing experiments as well as musical composition and performance tools. The need for a robust interface is exemplified by the difficulties of PC graphics cards, especially with regards to laptop PCs. Therefore, the objective is to produce an affordable stimuli unit that offers accurate flashing frequencies which is portable, programmable and compatible with music making software protocols (see Figure 26).

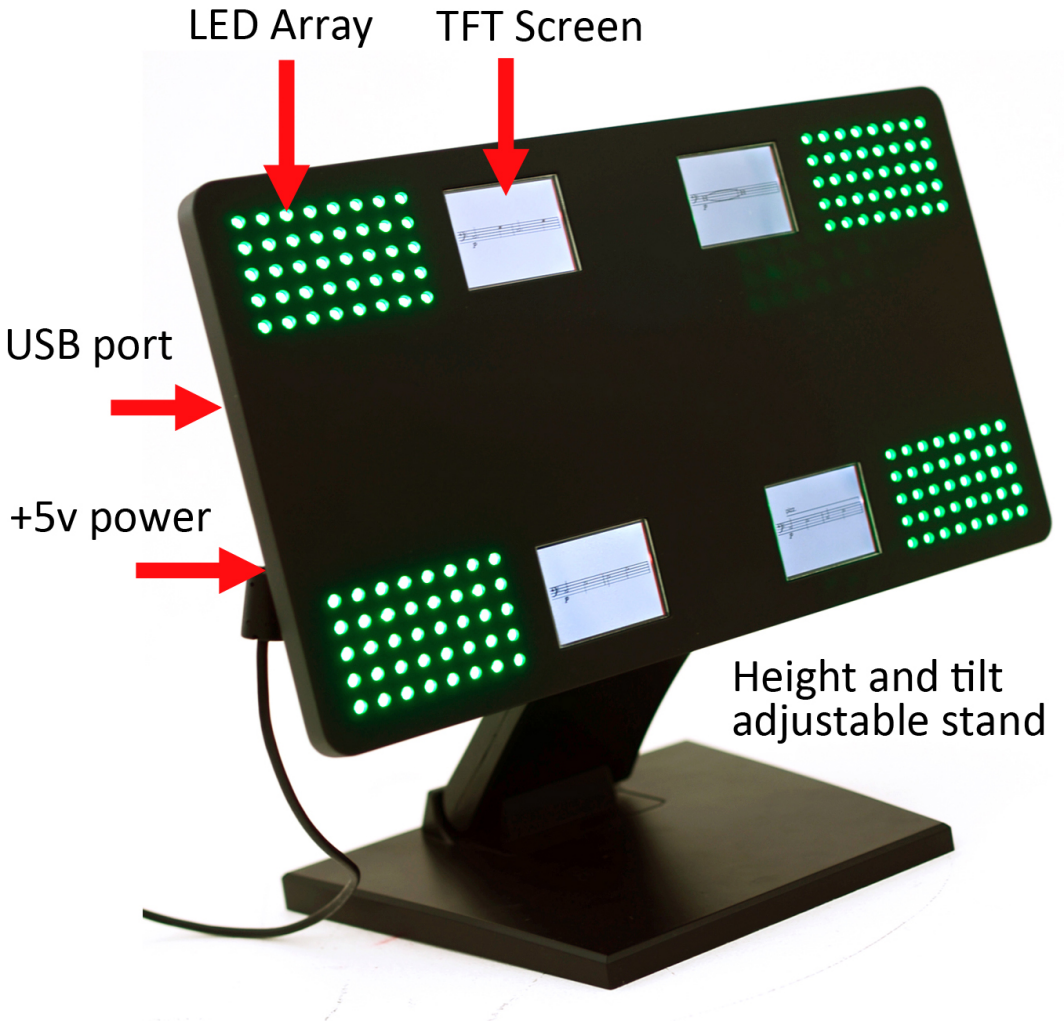

Figure 26. The external SSVEP stimulus unit. Sockets exist on the left hand side of the housing for connecting to a host PC and an external power source.

The functional aims of the unit are to:

1. Flicker LED icons ON/OFF at different but precise speeds, with specific colour and brightness
2. Display images alongside flickering icons in synchronisation with corresponding changes in the musical options available (see Figure 27).
3. Provide visual feedback to the user regarding positive SSVEP detection
4. Communicate with host PC for performance synchronisation to update images and present selection feedback

These are performed by code that is programmed on a PC and uploaded to the unit.

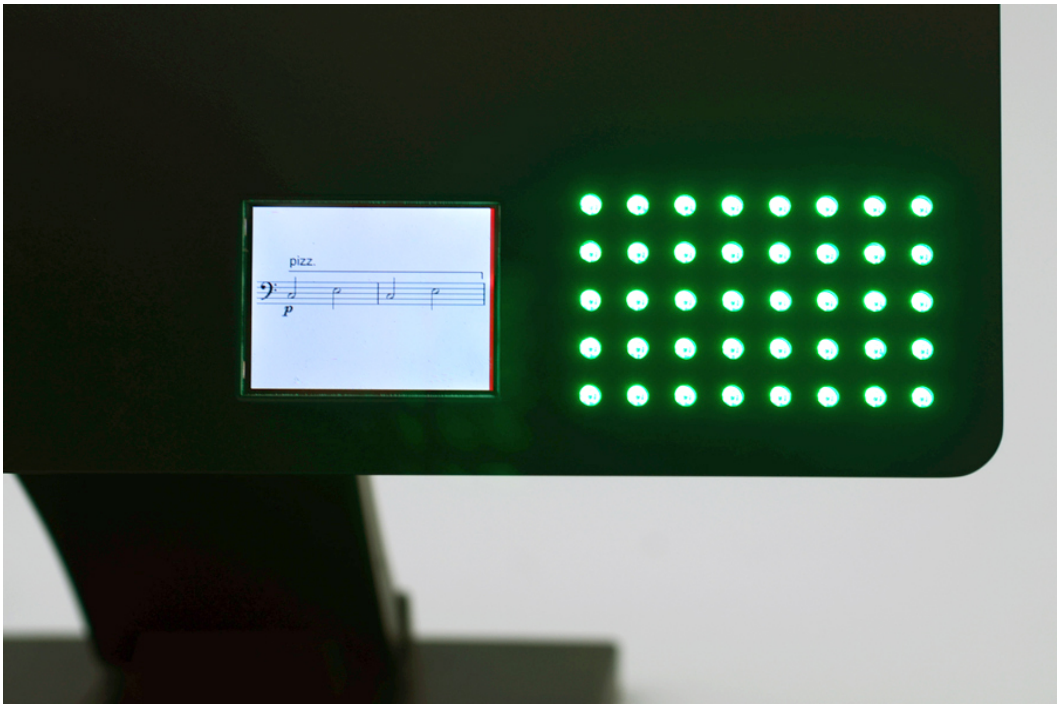

Figure 27. Detail from the external SSVEP stimulus unit, showing a short musical phrase displayed on the LCD screen.

5.2.3.2 Hardware design and components

Each SSVEP unit consists of the following components, in the layout shown in Figure 28:

- 1 x Arduino Mega 560 microcontroller board

The fastest performing Arduino board the Mega 2560 has the necessary input and output sockets for connecting all of the other components, as well as the largest amount of on-board RAM (Random Access Memory) of all the Arduino boards.

- 4 x Adafruit 40 RGB LED Pixel Matrix

The LED arrays are useful for prototyping and refining for user response as they feature adjustable brightness, and full RGB colour options.

- 4 x Adafruit 2.2" TFT screen

The screens are able to display full colour 24-bit BMP (bitmap) images at 240 x 320 pixels. The screens display images that correspond to the choices available by gazing at each LED array.

- 1 x Adafruit CC3000 v1.1

A wireless shield provides a platform for developing UDP communication over a wireless Local Area Network (W-LAN) with a host PC.

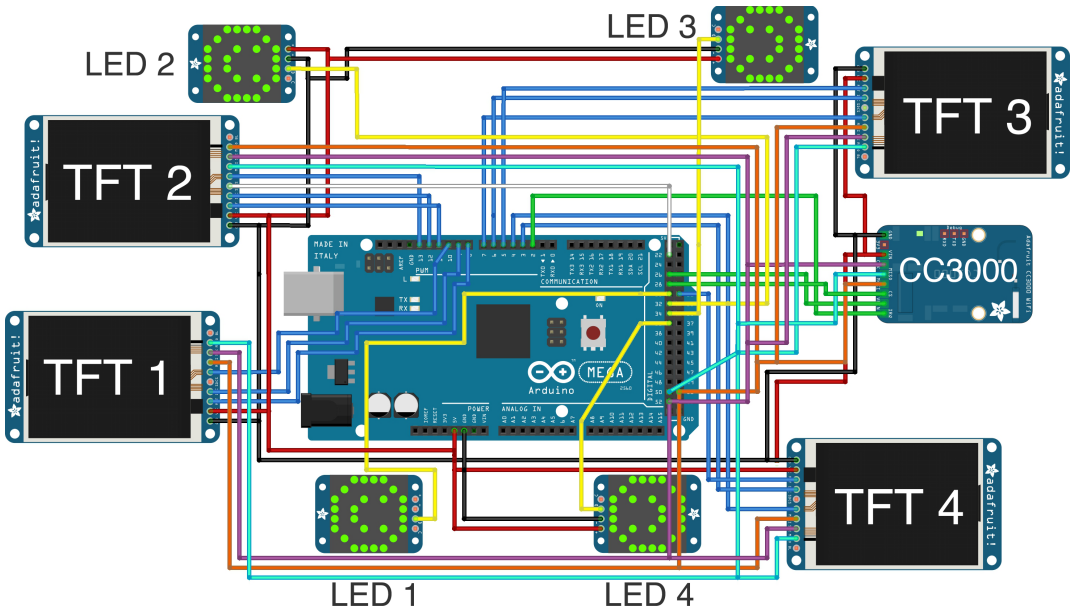

Figure 28. Schematic diagram of the external SSVEP stimulus unit's internal components and their connectivity.

The microcontroller allows for synchronous serial data transfer to be transferred quickly to multiple devices using a Serial Peripheral Interface (SPI). This allows for fast synchronization across the TFT screens and WiFi-shield when sending updates from the processor or from an external networked device. An outer case and stand were built to house the components and microprocessor board using an intuitive layout to present the LEDs and screens to the user. A plastic shell was designed using the measurements of the components to secure them in a small and symmetrical enclosure in a style similar to that

of a computer monitor. The body of the units were manufactured in China from a CAD design and were attached to a height and tilt adjustable third-party standard computer monitor stand. The LED arrays are spaced approximately 20cm vertically and 30cm horizontally apart (see Figure 26). The spatial proximity between the stimuli and the ability to adjust the visual angle via the adjustable takes into account the recommendations of Ng, Bradley et al. (2012) who suggest that superior BCI SSVEP accuracy is achieved when distance between flickering icons is greater than 5° (measured in visual angles).

In total, the components of the device cost approximately £240 at the time of writing, minus the custom housing. This price can be reduced, as not all of the components are essential for SSVEP control, such as the wireless shield and the TFT screens. Alternative and cheaper LEDs are also compatible with Arduino, as such a more economical system can be easily adopted.

5.2.3.3 Software

The functionality of the units is customisable through the programmable microcontroller at the heart of the device. Arduino is an open-source electronics prototyping platform designed for interactivity with third-party components such as sensors and displays like the LED arrays and TFT screens used here. The Arduino IDE (Integrated Development Environment) supports coding in its own language based that is based on C/C++. The environment is suitable for rapid on-board prototyping and development as it allows for programs (referred to as sketches[17]) to be compiled and then directly uploaded to the Arduino board. The single processor only allows for one task to run at any one time due to

[17] A sketch is built using three main parts, referred to as the structure, values and functions. The structure is made of two functions, setup() which runs once and determines initialisation statements, and loop() which runs continuously and contains the code to control of the Arduino board.

the absence of an operating system. Because of this programs that require multiple tasks to run at once need to factor this into account, for example applying a multi-threading technique on one processor. The hardware components used in the SSVEP unit each have an associated software library, and these need to be referenced inside a sketch to allow for interaction with the components. The library of the CC3000 wireless shield required re-writing in order to receive OSC communication via UDP. As such the unit can be used wirelessly during performance however communication via the USB serial port provides a more stable method of data transfer.

For synchronising the operations of the unit to music arrangements, communication data are sent from a software program on a host PC, either across a serial USB connection or across wirelessly via the WiFi-shield. The benefit of using the Arduino IDE is that a sketch can be customised for the requirements of different compositions, concert performances or experiments. Elements of a sketch can be repurposed in a process of continually improving development and testing (towards building) new ideas.

Different aspects of code within a sketch handle the four functional tasks outlined earlier in section 5.2.3.1. Task 1 is realised using a State Machine method to flicker the LED array ON and OFF with a loop that remembers the previous state of the LED array and when it last changed. Each time the loop runs the code checks whether it is time to change the state again using function that counts the run time in microseconds. The frequency and duty-cycle are easily customisable in the sketch to make adjustments for individual user preferences.

Task 2 occurs by reading BMP icons from an external SD card to each TFT display. The loading time of each BMP is, by default, approximately five seconds. With a combined time of 20 seconds to load four images this is considered far too long, on the other hand when icons are similar to previous ones a very quick load time may result in the user missing a

change. Reprogramming the Arduino so that images take a much shorter time to load provides a couple of advantages. Firstly, a user can read and study each image as it loads, taking into account the meaning of what is presented. In the case of *Activating Memory* each image displays a phrase of the music score, which needs to be read and considered against the other three images before selection takes place. Being presented with four instantaneously changing options can add an overwhelming element in an already sense-heightening situation. Secondly, the loading of images provides users with a break from the LEDs flashing, as the two functions do not occur simultaneously. Not only does this relieve the user's eyes temporarily but this can also be used as a cue for the user to study the changing of the icons.

Task 3, presenting real-time feedback, presents difficulties in assigning additional tasks to hardware, i.e. providing visual feedback, during flickering due to the single processor functionality of the Arduino. Although other multi-processor boards are available, such as the Parallax Propeller ASC+, which has the equivalent of 8 Arduino processors, they do not offer the number of sockets needed for connecting the components of the unit, or they are not compatible with the range of third-party hardware components required. Illuminating the corresponding LED array at the end of each selection window provides user feedback regarding which SSVEP channel was selected.

Task 4 has two possible methods. First, by modifying the library of the CC3000 wireless shield data can be received from the host laptop via OSC over UDP. An issue with delayed packets indicated that although useful for development a more reliable data transfer protocol was required, especially for concert performances when integrated with a synchronised system. The second method is to use a USB connection between the host PC to the Arduino board. This allows for a more stable method of communication, but unlike the wireless shelf must be hard-wired. A custom built patch in Pure Data provides

seamless interaction between the transformation algorithms, the global clock and the EEG feedback.

For *Activating Memory* the code within the unit's sketch is written to perform tasks sequentially in the form of a routine that synchronises with the periods of EEG measurement and the window changes. In other applications the routines can be customised, in particular with regards to timings. The sections of the routines used in *Activating Memory* (for one BCMI system of the four) is summarised in Table 13.

Routine	Musical Clock	Transformation Algorithm	SSVEP unit
1 (init)	On bar n=1 beat n=1 (bar 1 beat 1)	Begin collect EEG data	Start LED flicker until bar 8 beat 7
2	On bar n_1=(n+8) beat n_1=(n+7) (bar 8 beat 7)	Determine user selection	Display user selection on corresponding LED array
3	On bar n_2=(n_1+9) beat n_2=(n_1+1) (bar 9 beat 1)	Reset counters for determining user selection	Display icons then start LED flicker
Repeat from 2			

Table 13. Programming routine for SSVEP stimulus unit to perform *Activating Memory*. The global clock sends data to the musical clock of the host PC that triggers a series of events, from left to right of the table's columns within each routine.

5.2.3.4 Observations on Performance

Overall the hardware SSVEP unit performs consistently well. The programming code required considerable optimisation to perform the routines required in *Activating Memory* robustly and reliably, as such testing was conducted over extensive trials.

A significant issue that was observed regarding the microcontroller's internal clocking speed. It was found that precision in LED flickering using the controller's internal timer, although consistent, occurred at approximately 0.3Hz faster than specified in the code. This appears to be the fault of the processor for a number of reasons. Firstly there are no obvious lags or late arrival blinks at the end of running a program. Secondly the issue occurs regardless of the number of LED arrays connected (the same outcome occurred with one up to 8 LED arrays flickering at once), and adding or subtracting units doesn't affect the anomaly. Once this was detected the problem was overcome by adjusting the flashing rates in the unit code to compensate, although likewise it might also be dealt with by adjusting the bandwidth of the EEG filters accordingly.

Particular difficulties arose from integrating so many components in one system with the Arduino board. With 9 components sharing the SPI bus parsing data required efficiency and simplicity, especially with regards to flickering icons and loading images onto the screens, which uses up vital RAM allocation. A specific version of the CC3000 WiFi-shield was required (v1.1), as the original version (v1.0) was found not to be able to run on the hardware SPI.

5.3 Activating Memory

5.3.1 Overview

In 2013 I worked with composer Professor Eduardo Miranda on a BCMI performance piece, *Activating Memory*. Collaborating together on the overall concept, Prof. Miranda composed the musical score and I developed the hardware and software to create a multi-brain BCMI system.

The system for *Activating Memory* is built for a BCMI quartet and a string quartet. The overarching control objective of the *Activating Memory* BCMI is to allow each member of a BCMI quartet to choose a musical phrase from a series of four options which a corresponding member of a string quartet then plays. Whilst the musician is playing a phrase the BCMI user chooses the following phrase to be played. When the system updates at the end of each window the new phrase is presented to the musician and four new options are presented to the BCMI user. This process of continues throughout the piece. Each member of a BCMI quartet is furnished with the SSVEP-based BCMI system, which enables him or her to select a musical phrase. Each member selects a phrase for the string quartet, and the corresponding score is displayed on a computer screen for the respective string performer to sight-read during the performance. In order for the system to create a coherent piece of music where the musicians performing in-time with each other the SSVEP selection processes and the score displays for the musicians are synchronised to a metronome to allow for a fluent musical performance. Another important objective of the project was to create a platform where the BCMI users could not only work alone in selecting music to be played, but also allow work together in selecting music that is sympathetic (or even unsympathetic depending on their preference) to other individual elements of the string quartet either in various combinations of instruments or as a whole

ensemble. This creates a space for musical interaction between BCMI user, solely through brainwave control.

Extending solo control in a single-user BCMI a multi-brain system offers new potentials for sharing control and creating shared musical experiences. For example, users can take it in turns to affect control at different times during the piece, or alternatively users can control different elements of the same musical part at the same time. The concept behind *Activating Memory* arose via feedback from therapists at the Royal Hospital for Neuro-Disability, London given during an earlier collaborative BCMI project. One of their suggestions about developing new technology for control was how patients are often presented with new technology that provides a one-to-one interaction, often between patient and therapist/carer. Instead of this it was suggested that a system that allowed for patients to interact together, especially in a medium as expressive as music, would be far more beneficial. This notion underpins the design of *Activating Memory,* which provides a foundation for future investigations into behavioural patterns between patients interacting with BCMIs.

Activating Memory also aims to improve on the performance aspect of BCMI. *Activating Memory* expands brainwave control into the acoustic realm of music with each BCMI performer connected to a musician. During performance this can provide a strong visual connection between brainwave control and music, as well as a more interesting spectacle through the physicality of the sting quartet. The choice of using acoustic instrumentation was to present BCMI technologies on stage as less insular and inaccessible, in a way that demonstrates its musical control functionality as clearly as possible. The gestural and human characteristics of a string quartet coupled on stage with a physically static BCMI quartet is designed to act as the expressive extension of the BCMI quartet. In fact, the stage design itself aims to help portray this to an audience. Each member of the brain quartet is positioned in front of his or her corresponding musician so that the BCMI quartet sit in a

row across the front of the stage with their backs to the audience. The string quartet faces the BCMI quartet as well as the audience in the traditional arrangement of L-R, 1st Violin, 2nd Violin, Viola and Cello. With this layout the audience are exposed to two things, firstly the BCMIs quartet's flashing SSVEP stimuli and the associated images of the user choices (although viewing the exact details of these images is rather difficult for those in the audience), and the relationship between each BCMI subject and musician through their positioning, shown in Figure 29. This setup accounts for the traditional positioning of a string quartet (semi-circle fashion) with the BCMI quartet bolted-on, so to speak. The intended visual result is one of the string quartet representing the traditional musical element of the piece and a BCMI quartet acting as the modern reflection of the traditional, taking over (literally in terms of the stage) with its multitude of wires, cables, pieces of equipment and computers. It portrays the integration of technology and tradition, without complete invasion and the will to replace the old ways, a new harmonious relationship so to speak. This relationship certainly intrigues the audience and increases their curiosity.

For *Activating Memory* the SSVEP technique is used again, but unlike *Flex* only one method of primary control exists, which is centred on finite decision-making for direct user selections over four options. Therefore the mapping strategies used for *Flex* that explore creative uses of mappings, and account for noise and false positives are no relevant here. And a more robust, accurate system of control is required than can reliably confirm user selection. Corresponding elements of the *Flex* BCMI were updated and improved in an attempt to provide greater accuracy, in particular the EEG measuring hardware and the method of presenting and rendering flickering icons. To extend the use of the BCMI to other users, aside from myself, a clearer and more universal approach to visual representation of user choice and feedback was adopted. To develop a BCMI for users across a range of musical and technical backgrounds the usability of the system needs to be clear and simple to for success to be accomplished, with minimal effort and

training. The presentation of visual elements, representing BCMI user choice, was carefully considered, as well as how user choice was transformed into musical notation for musicians. In early iterations of *Activating Memory* graphic symbols were presented next to flickering icons to represent musical selections, but through trials with users the participants preferred being able to see actual phrases of the score that are being selected and presented to the musicians. Even without the ability to read music comprehensively most participants felt that they could interpret characteristics of the music from the layout of the notes. Musical descriptors such as busy, fast, silent, slow are implied in the contrasting phrases, and this can be a useful gateway towards an understanding of musical notation to those with little or no previous experience of reading music.

Figure 29. Photograph of the stage layout of *Activating Memory.* At the 1st International Workshop on Brain-Computer Music Interfacing (BCMI 2015), June 2015.

Again, as with the other BCMI systems in this thesis, at the time of development there were no off-the-shelf products that could perform the objectives of *Activating Memory,* and

certainly none that could facilitate multi-brain SSVEP control for music. Therefore a customised multi-brain BCMI system was required to implement *Activating Memory*.

5.3.2 Design considerations: Shaping music performance with a dynamic digital score

The musical design for *Activating Memory* is built around the capabilities of the system and the limitations of such a situation. The piece replaces a traditional paper-based musical score with a dynamic electronic score, and as such some fundamental usability rules are taken into account. Musicians do not read a score on a note-by-note basis and can therefore not be expected to sight-read a score that updates in such a way. Instead, a musician intuitively reads ahead of the current position when sight-reading, with a distance depending on the complexity of the score. As such, for a musical score presented electronically a measure of time delay is required for a musician to read any changes ahead of time instead of instantaneously. In order to provide this the score for *Activating Memory* displays 12 seconds of music across four bars over two lines at 80bpm. During performance a visual metronome counter counts from 1 - 8 beats coinciding with total beats in the active line, which is always highlighted (see Figure 30). The squares next to the metronome counter also form part of the visual metronome and flash on every beat in each bar from 1 – 4. Combined with an audio metronome these visual tools aid playback synchronisation across the four musicians. The upcoming line of music is visible but always greyed out and this results in the top and bottom lines alternatively displaying the active and next line of music. Therefore to follow the score any upcoming changes are always presented 6 seconds ahead; a straightforward feat for most accomplished musicians.

The result is a dynamic score that always presents the current 2-bar phrase and the upcoming 2-bar phrase always from a lead-in of 6 seconds ahead. In practice this means that the BCMI user selection must be recorded 6 seconds before the musician then

performs the result. During this delay period the next four options are presented to the BCMI user to consider.

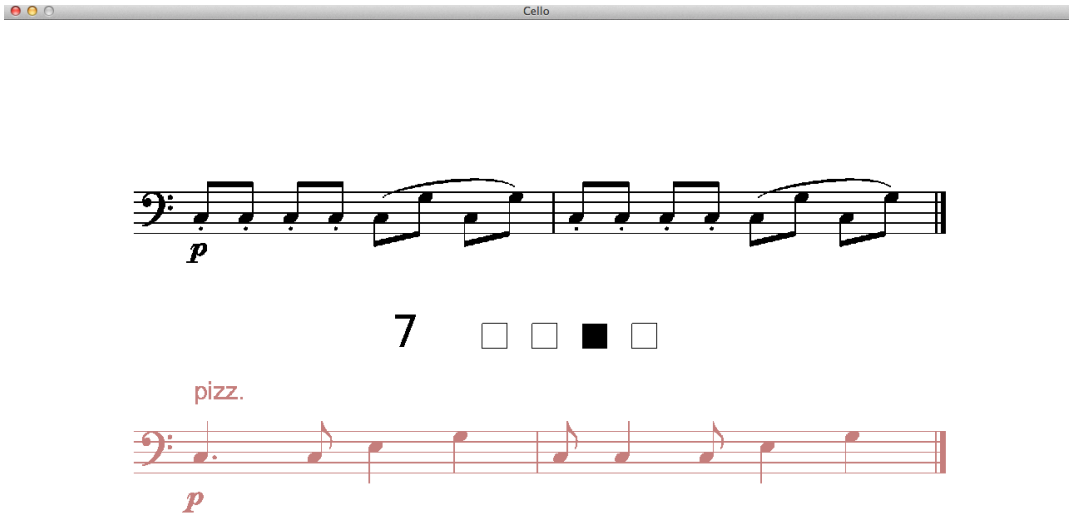

Figure 30. The score display window for cello in *Activating Memory*. The current position is the 3rd beat in the second bar (7 across the top line). The upcoming line is dimmed (in red) and will change to black (active) in 2 beats time.

A score that updates every 6 seconds would be extremely taxing for musicians to keep up with, and more so for the BCMI users who would only have 6 seconds to review four options and make a selection detectable by the system. Instead, the composition is broken down into 2-bar long (6 second) musical phrases. These phrases are presented as images on the TFT screens with associated flickering LEDs for BCMI user selection. During *Activating Memory* each two-bar phrase repeated four times in a window lasting 24 seconds. For each window a BCMI user is presented with four 2-bar phrases to select for the next window. During the next window they choose from four new options for the next window, and so on. This way the BCMI user is always selecting the music for the upcoming window. A performance of *Activating Memory* lasts for 33 windows.

The manner in which the system influences the composition and performance results in a generative approach to music making that has roots in a musical age far pre-dating

computers. Musikalisches Würfelspiel, a music style of German origin, can be considered as an early form of generative music that was popularised in 18th Century Europe. A composer would use dice to randomly select small sections of pre-composed music resulting in a piece that would differ in arrangement every time. Mozart's K6.516f, for instrumental trio, is widely thought to be derived from this method, and in another work attributed to him the score's accompanying commentary begins its instructions with the line 'To compose, without the least knowledge of music, so many [scores] as one pleases…'(Mozart 1793).

5.3.3 BCMI System design

This section outlines elements of the *Activating Memory* BCMI, which can be considered as four separate BCMIs brought together, and discusses features and specifications of the equipment used, such as synchronisation and hardware and software platforms that differ from the *Flex* BCMI.

5.3.3.1 Overview of elements

The BCMI system for *Activating Memory* is comprised of a number of components. The system can be broken down into four individual BCMI systems, each slave to a global master clock. Each of the four BCMIs comprise:

- **SSVEP stimuli.** SSVEP stimuli is provided by the external SSVEP stimulus unit (four in total – one per BCMI user). Within these units, four flickering icons are shown next to images of the corresponding musical phrases. These represent the selection made when the user gazes at the flickering icon. The frequencies are chosen from the best performing 4 across all of the users in the experiment in section 5.1; 7Hz, 7.5Hz, 8Hz, 12.5Hz. A feature is added whereby the images update to reflect four new options available to the user, occurring at the end of every

window. Therefore, even though the maximum number of simultaneous choices is four, by regularly changing the choices on offer the user chooses from over a hundred options during the course of a performance.

- **EEG measurement.** Platform 1 (section 2.3) is used for measuring EEG. The g.tec dry electrode system was chosen for its fast response time, which given the nature of the finite window lengths of *Activating Memory* was useful to provide a quick method of detection once a user had made their selection and begun icon gazing.
- **SSVEP classification.** Raw EEG is pre-processed with a notch filter to reduce mains interference at 50Hz. Data is filtered via four parallel bandpass filters to extract the power within each narrow band corresponding to stimuli frequencies, as outlined in section 3.2.1.1.

  As with the *Flex* BCMI a linear threshold classification system is adopted for calibration, as this allows for requiring minimal training. Again, the system provides a calibration function to help determine baseline thresholds. In the *Activating Memory* BCMI thresholds can be adjusted manually via a user interface to account for changes brought on by fatigue, different impacting environmental factors or when changing location. As before threshold values can be stored for future recall. Positive SSVEP detections are passed to the transformation algorithm to determine user selections. Eventual system detections are also sent to the external stimulus unit to provide visual feedback to the user.
- **Transformation algorithm.** The transformation algorithm is used to determine a user's choice of one of the four options during each window. Various approaches were trialled before the final method of deriving user intent was adopted. The transformation algorithm calculates which of the four SSVEP channels remains positive for the longest time during each window. This method was used for two reasons. Firstly, it allows a user to override their previous decisions made within a

window. This creates an *undo* or *backspace* type of keystroke function. A user can gaze at multiple icons during a window but the one that is selected is the one gazed at for the longest time. Therefore, if a user begins to select at one icon they can change their selection so long as the gazing for the new icon takes longer. The second reason is that this is quite a useful method to minimise false positive detections from noise being interpreted as user intent. On the whole false positives caused by noise were found to last less than 10 seconds (the time window in *Activating Memory* for selection to take place). By confirming selection by icon gazing for as long as possible false positive inference is reduced. The time of each gazing period is recorded from when a channel's amplitude increases above a^{min}, until it decreases back to below a^{min}. A count value, in millisends is stored. If any later positive detections occur during the same window the timer continues to count upwards from the previous count value. There is no limit to how many times a channel's timer may start and stop counting (although during a 10 second window the maximum number of positive detections achievable was approximately 3), and the timers on different channels can count at once. At the end of a window the count values of all four SSVEP channels are compared, the channel with the highest value determines the selection, and then the values are reset to 0. The transformation algorithm maps the selection command to both the corresponding musical phrase for the score display, and to the external SSVEP stimulus unit to feedback the selection to the user. After the selection is determined the timers are reset to zero for the start of the next window. It is worthwhile pointing out that a fifth control option is available by the act of not icon gazing at all. If this occurs the system selects the next musical phrase by randomly choosing from the four options. This was implemented for two purposes; to provide a user with moments of rest (in particular with regards to

their eyes) in the knowledge that the system would take over for them, and to provide a back up scenario should either positive SSVEP go undetected or if a fault or error in the EEG hardware or classification software should occur prior resulting in no detections. The first of these two factors is particularly useful for users with disabilities that limit their attention or tiredness levels, as was found in preparation for a performance with the *Para-Musical Ensemble* (discussed further on). Furthermore, it also allowed all users to have periods of respite where they could simply enjoy the music. Periods that could be chosen at a user's own will, and at any time.

- **Score display.** The phrases selected by the transformation algorithm are presented on an external computer for the musician to follow. The window is resizable to allow the musician to account for distance and personal taste. The score window is shown in Figure 30.

5.3.3.2 EEG Hardware

Activating Memory uses four g.Sahara electrode systems each comprising a brain cap, Sahara dry electrodes, a Sahara amplifier, a g.MOBIlab+ digitiser and the g.tec Matlab API for developing processing tools, otherwise known as platform 1 from section 5.1. This is coupled with a laptop for each of the four BCMIs. The ability to transmit raw EEG from high quality electrodes and amplifiers to a laptop computer (in this case transmitting EEG using Bluetooth via a USB Bluetooth receiver) is a big step in providing reliable EEG measuring for a portable BCMI system. It improves transportation and therefore concert preparation significantly. Even though users have approximately 10 seconds to make an SSVEP selection, platform 1 was chosen for *Activating Memory* because of the faster response time available, allowing users to stare at flashing icons for shorter times. Within each 24-second window the first 12 seconds are used for image loading (on the screens)

and for a user to study the phrases and make their choice. Over the remainder of the window the icons flash and EEG is recorded, and finally selection feedback is shown via the LEDs and the SSVEP selection is used to choose the next musical phrase. A two-bar window overlap exists to show the musicians the upcoming phrase. A further benefit of using four self-contained BCMIs for *Activating Memory* is that each BCMI can be treated as a separate entity. No amplifiers are shared between users nor are any individual BCMIs dependent on the elements of another one. All four BCMIs are almost identical, minus the images of score phrases for the stimuli unit screens, and the score display windows for the musicians. And this allows for a deployment of the system configurations across the three remaining BCMI systems once any development changes or updates are complete on one first BCMI.

Each of the four BCMIs use a Toshiba laptop PC with 8GB RAM and an i5 processor. The PCs are placed under considerable processing strain due to the number of tasks performing at any one time. This raises issues with performance latency, especially with regards to an internal clock used for synchronising a performance and controlling a visual metronome. It was discovered that when using four clocks hosted on each PC there were significant latency across the PCs, even when an external networked device initiated the clocks. Such a result is unsuitable for musical performance. Instead, a master PC synchronises all the BCMI PCs to its own clock, separate from the four BCMI PCs. By doing this even if an individual PC's processing begins to lag at certain times, the master clock always provides an accurate update once the PC in question eventually catches up (in practice this is never longer than 1.5 seconds and this is manageable by the musicians). Other issues identified that contributed to latency were caching and reading of large image files, and using the Toshiba digital DisplayPort™ for connecting an external monitor. To counter these issues the image processing software pre-loaded all the images into the local

cache automatically on the application's start-up and the analogue VGA port was used to display the musicians' score on an external monitor, albeit with poorer visual quality.

5.3.3.3 SSVEP stimulus units

Four external SSVEP stimulus units were designed and built to meet the specifications of performing *Activating Memory*. They feature 4 x LED arrays that provide four flickering SSVEP stimuli. The LED arrays also provide users with visual feedback regarding SSVEP channel detection. Here, the LED array of the selected channel turns red whilst the remaining three turn blue at the end of each window. The units also house 4 x TFT screens to display the images representing the choices associated with each SSVEP channel (and the corresponding LED array). To recap, in the case of *Activating Memory* the images shown are 2-bar phrases of the score (1 per TFT and 4 per window). Each unit connects to a host PC via USB for data transfer. The host PC sends commands for updating the images on the TFT screens and for feeding back the SSVEP channel detection from the transformation algorithm at the end of each window. A dedicated external power supply is used to provide enough current (up to 10 amps) and 5v power to the units.

5.3.3.4 Software

Activating Memory makes use of two software platforms, Matlab and Pure Data, which are both ideally suited for the development of both EEG processing tools and real-time audiovisual control respectively. Matlab performs EEG pre-processing and filtering, as outlined in section 3.2.1 and outputs the resulting data streams from the four SSVEP channels internally within the PC to Pure Data for classification by the transformation algorithm. Data is output from Matlab using the OSC protocol via UDP. The Pure Data patch contains a number of sub-sections for specific functions. These include:

- Receiving EEG data from Matlab.

- Input SSVEP a^{min} threshold and a basic user interface to allow BCMI users to adjust a^{min}.
- Receiving counts from the master clock and applying master clock counts to moving through windows, display the metronome and toggle the changes in updating the active/passive score line in the score display window.
- Applying the transformation algorithm to determine user choice within the window.
- Applying random selection across the next window's four options if no user choice is detected.
- Mapping user choice to correct image file for loading in the score display window.
- Changing the background colour of the display score during the final two windows. (amber, red then black at the end) communicating the end of the piece to the musicians.
- Managing the external SSVEP stimulus unit serial connection and sending data for image updates and feedback at the end of each window.
- Presenting a GUI for performance mode. Including global controls for configuring external SSVEP stimulus unit connection, solo performance mode (useful for testing), and passing/blocking EEG data from Matlab through to the transformation algorithm.

5.3.3.5 Network metronome and audio synchronisation

A Local Area Network (LAN) router synchronises all four BCI system laptops to the master PC. Each of the four BCMI PCs is assigned a static IP address and clock updates (read by multiple counters in the receiving Pure Data patches for determining beat and window information), start, stop and reset commands (stop and reset commands are used during rehearsals and testing) are sent via the TCP protocol and received over each IP address via

a dedicated port. For data passed internally, from Simulink to Pure Data, different ports are used to separate data across communication channels (see Figure 31).

To compliment the visual metronome an audio metronome, by means of a click track, is sent from the master PC via an amplifier to a pair of in-ear headphones for each musician.

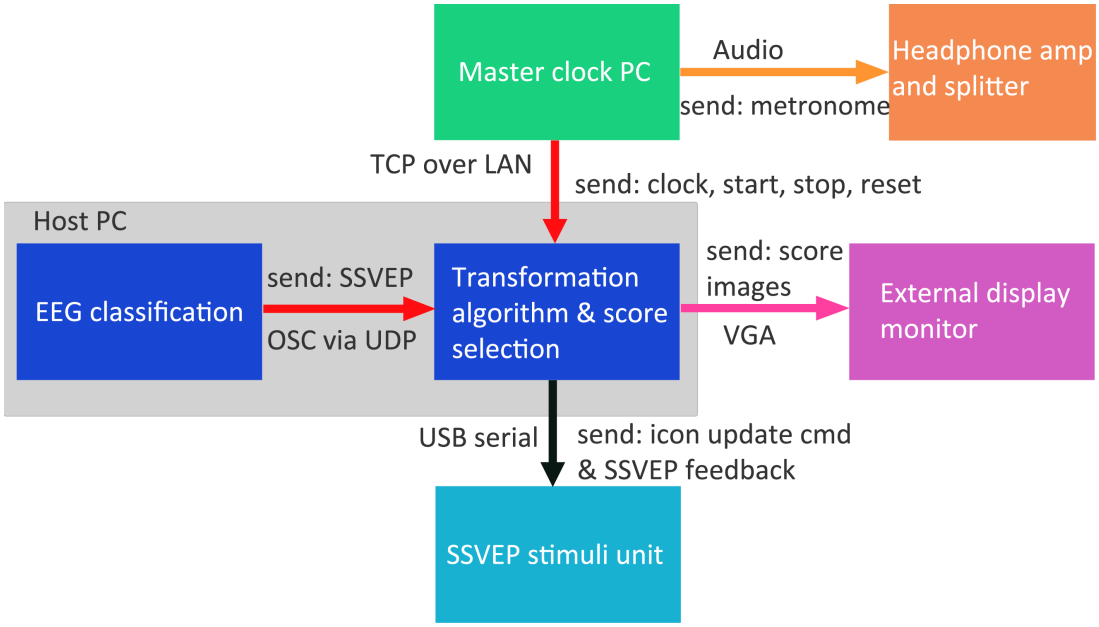

Figure 31. Serial, network and audio connectivity for each of the four BCMIs used in *Activating Memory*.

5.3.4 Musical mappings

The mappings of *Activating Memory* employ a straightforward one-to-one approach. And although the four control options change every window, overall only one music parameter is being affected, the score (although the musical changes within the phrases are very detailed). There are no further rules applied to determining mappings, such as interpreting previous selection patterns or amplitude control, the changing options are fixed, synchronised in time to the metronome, as they are relative to the expected updates every 8 bars. It is interesting to note that the musical mappings of *Activating Memory* are less comprehensive than those of *Flex* but by taking into account the of the combined

outputs of the four BCMIs the musical possibilities are far greater with control from four users. This simpler approach to mappings is beneficial to creating a successful system when there are so many other variables to take into account, in particular the integration of four musicians. This approach is not only for necessary for designing musical coherence through the extensive range of the possible combinations of the phrases but also helps in translating the method of control (through phrase selection) to a range of audiences. In all there are 256 (4^4) possible combinations of phrases per window for the four BCMI users as a whole. Unless explicitly coordinated this guarantees each performance to be different from the last as the total possible combinations throughout a performance is staggeringly excessive at 256^17 (256 choices per window with 17 individual windows (some windows occur more than once during performance).

5.3.5 Observations and discussions, including user feedback

A concert performance of *Activating Memory* requires an engineer to setup, calibrate and prepare the BCMI users. The engineer also needs to prepare the system, and oversee performance of the system from sound check through to concert. The engineer operates PC master clock PC to initiate the performance and begin the metronome's 2-bar lead-in. The first musical phrase is selected randomly from window 1's options and the first selection for each BCMI user is from all four options in window 1, providing an initial option to repeat the first phrase if desired.

Although only used by one of the BCMI users (added by request) a self-calibration tool is a useful one in practical terms. It not only allows a BCMI subject to fine-tune their SSVEP thresholds at their own convenience (which can differ between sessions) but also takes the pressure away from the engineer during a production giving them one less task to perform. In-line with one of the key areas highlighted in the summary of the literature review in chapter 2 it is important to address user experience factors BCMI design.

Anecdotal feedback from the BCMI users for *Activating Memory* was gathered about their experiences terms of measuring the success of the system. This can be considered alongside the more quantifiable successes in terms of providing EEG accuracy with the external SSVEP stimulus unit. The six BCMI users in the first two performances of *Activating Memory* were all healthy subjects between the ages of approximately 30 – 50, one female and 5 male. They all have a moderate to strong musical and technical background. Five of the users reported a high level of success with regards to the system recognising their selections, whereas one user reported a medium level of success (i.e. they noticed a medium level of incorrect SSVEP detections). The side effects of the technology that this feedback addresses positively correlate RQ4 and the notion of collaboration with BCMI. For example, with regards to the collaborative impact on his experience, user F reports that:

> *"The choices of the others certainly influenced mine and at times it was very exciting to have the impression of shaping the performance together."*

He goes on to say:

> *"After improving my skills with the system I felt more connected to the music. Hearing the part I selected being performed by the musicians on stage has sometimes felt very rewarding and engaging."*

This awareness of a connection not only with the music but also with the performers is reinforced by user R, who says:

> *"I felt really connected with the music being performed…. I believe that the composition process, considering the selection of the parts and the respective sets of music bars, was really important to create expectations, allowing the feeling of connection with music and also allowing the connection with the other performers."*

These statements indicate that there are times when the user felt very excited and engaged through the collaborative processes. This engagement can be linked to an improvement in ability, resulting in a greater connection to the music. This specifically goes towards addressing RQ4 with regards to developing a BCMI system that provides a

space for collaborative music making. The statements also imply that the learning element, which improves ability, offers a reward. Having a musical incentive that is pleasing to the user is a very satisfying outcome of the system; a success of both the compositional and BCMI design.

On the other hand user F also reported that:

> *"However, other times I felt more disengaged, perhaps because it takes quite much effort to listen to the music being played while choosing what is going to the played in the next few bars. I guess it takes practice to get the right flow, just like with a traditional musical instrument."*

Which suggests three things:

1. The system takes time to master.
2. There should be times when less cognitive effort is required. Perhaps the 5th control option is not effective enough.
3. A user is able to consider playing a BCMI similar to learning a musical instrument. This ties in with the notion that a BCMI has the elements of a DMI, an idea raised earlier in chapter 2.

Finally, R goes on to say:

> *"Some frequencies of the blinking lights are easier to lock onto than others"*

Overall, the feedback provides some positive suggestions for future versions, in particular a focus on user training; perhaps providing time for practice is necessary for *Activating Memory*. The last comment, with regards to certain flickering frequencies being easier to "lock onto" suggests that some icons produced more accurate responses than others (as the user was referencing the success of detecting gazing). The comparison of variations in which individuals respond differently to different SSVEP frequencies has provided the basis for previous BCI research (discussed in chapter 3), and helps inform the experimental paradigm used further on in this chapter to monitor the variation within a

small number of participants. Ultimately this is a worthwhile consideration for future BCMIs to cater for individual responses as certain frequencies may perform better than others. Alongside the self-calibration tool built for *Activating Memory* a BCMI with an automated classification tool to identify optimal frequencies would help improve accuracy and ultimately benefit user experience.

In July 2015 a version of *Activating Memory* was performed at the Royal Hospital for Neuro-Disability, London, that allowed severely physically disabled and non-disabled musicians make music together (see Figure 32). *The Paramusical Ensemble* consisted of a BCMI quartet made up from patients, all with conditions resulting in paralysis, and a string quart of able-bodied musicians. This performance exemplifies how BCMI technologies can be used by people of all physical abilities to take part in active music making.

Figure 32. Photo of *The Paramusical Ensemble* rehearsing for a performance of *Activating Memory*.

5.3.6 Development issues

The g.tec EEG hardware presented a number of issues, some easier to resolve than others, which are useful to address for future research interest. The g.tec EEG hardware suffered from a lack of electrical grounding that produced noise in EEG data. By holding both the Sahara amplifier and the g.MOBIlab+ unit in a user's hands a ground loop is effectively created, lessening the effects. Particular care of monitoring and eliminating unwanted localised interference points such as lighting and power cables, additional Bluetooth devices, and network cables was also still necessary. Unfortunately there were problems from the outset with sending EEG data via Bluetooth. These could have been avoided if the serial cable between the MOBIlab+ and the host laptop was functional, however this feature was not available from g.tec at the time of development. Instead the Windows Bluetooth drivers required rewriting to allow successful data transfer in Matlab.

The g.tec API provides a toolkit for EEG detection, pre-processing and SSVEP filtering in Simulink. There are however no objects, protocols or features for mapping the EEG data to musical features or score selection within the Simulink (or any other) environment. As such, a bespoke Matlab function for sending data via the OSC protocol sends EEG data in real-time to Pure Data. Likewise, further bespoke software was developed from scratch including the transformation algorithm and phrase selection functions. The code for operating the stimuli units and the master clock (including the metronome) was also developed.

5.3.7 Conclusion

This section of the thesis has reported on the success of a multi-user BCMI system that provides control over a synchronised score for acoustic instrument performance. Results from the experiment conducted in section 5.1 inform the development of the *Activating Memory* BCMI, taking into account the accuracy and response time available with the

external SSVEP stimulus unit. A short documentary video illustrating the development of the system, the thoughts of the musicians and excerpts of a concert can be is contained in **Appendix 1.**

In summary the research has lead to:

Developing bespoke **software** that:

- Communicates data from Simulink to Pure Data using OSC via UDP.
- Performs as an all-in-one SSVEP BCMI platform that determines user choice, selects a musical phrase and presents the result in a dynamic score to a musician.
- Allows for these separate BCMIs to be integrated in a modular fashion to create a multi-brain BCMI.
- Synchronises the process of detection, calculation and musical mapping within a concert performance environment across a LAN.
- Provide a user calibration tool to set SSVEP power thresholds.
- Translate a musical concept into a realisation for a concert performance.

The design and build of SSVEP stimuli **hardware** that:

- Presents images for user selection.
- Presents four independent SSVEP stimuli via flashing LED arrays associated to images.
- Provides user feedback corresponding to SSVEP selections.

The research presented here demonstrates not only that a multi-brain BCMI can be realised (addressing RQ4) but also that the technology can perform in concerts outside of laboratory conditions (addressing RQ3). In order to gauge the success of the system it can be reasonably argued that all of the objectives of *Activating Memory*, outlined in section

5.3.1 are met (the overarching control objective, the musical objective and the performance objective). Furthermore, the anecdotal feedback of the BCMI users indicates that such a system can introduce a useful connection to the music that is generated as a result of participation, even if at times the system can be overwhelming.

It should be noted that although the method of detection SSVEP is not only expanded to encompass four users in one system, the actual control method of user gazing remains the same as in the *Flex* BCMI (aside from the EEG processing employed). Four channels are available and control can be applied only to one channel at a time. *Activating Memory* marks a milestone in the development of BCMI systems. However, to go beyond what is has been achieved with accurate SSVEP and multi-brain control requires this research to look beyond this one method of control to other methods that can also be exploited for creative music making as well as being potentially combined with SSVEP control to provide simultaneous control across additional dimensions.

5.4 Summary of chapter

This chapter has presented research towards providing a stable SSVEP control platform within a portable BCMI. A new external SSVEP stimulus unit is proposed and an a comparative experiment is presented that confirms the SSVEP accuracy available with the unit and goes someway towards proving the hypothesis that although consumer grade EEG devices provide some measure of accuracy, more sophisticated EEG hardware still offers far greater accuracy under similar conditions. This area of the research directly addresses **RQ3** where the stimuli units and corresponding SSVEP have been improved upon the previous *Flex* BCMI towards use outside of laboratory settings for music performance. This chapter then presents a technical report on the new unit, outlining the unit's components, programming structure, pathways of communication and interoperability with other elements in in a BCMI.

Results from section 5.1 inform the design of the multi-brain BCMI used for Activating Memory. Activating Memory demonstrates how a BCMI system can integrate SSVEP brainwave control from multiple users simultaneously, and how a BCMI system can be expanded to include acoustic instrumentation for live performance. The success of this BCMI is measured through user feedback and concert performances, in particular with the *ParaMusical Ensemble*, where four paralysed patients with minimal training make up the BCMI quartet in a live performance with a string quartet. This goes some way towards addressing **RQ4** through the exhibition of a creative and novel approach to combining BCMI user control. In addition to this *Activating Memory* also exhibits a custom made external SSVEP stimulus unit, designed to improve SSVEP control. A summary of the achievements of this research is outlined in section 5.3.7. The mapping strategy used in Activating Memory, to allow users to control the score of a live performance presents another novel approach to mapping brainwave to music control, addressing **RQ2**.

Although the equipment of the *Activating Memory* BCMI is increased four-fold, it is still relatively portable making transport to concerts still easily achievable, and one SSVEP BCMI system now only requires one laptop PC, as opposed to *Flex's* two. As an example of the portability the entire system has been transported via public transport a number of times for performances across the UK by one person.

This chapter presents a much-improved SSVEP BCMI that is robust, easy to use and suitable for performance acoustic music, for single or multi-user control. However, as the focus of this research has been on stabilising the SSVEP technique the amount of control on offer using this technique remains the same. Essentially it is still a monophonic form of control, i.e. one-to-one or one-to-many mappings. Now that the SSVEP technique has been optimised for greater robustness using the external SSVEP stimulus units, the next chapter looks beyond SSVEP to another method of extracting brainwave control by monitoring affective states. The aim of exploring this area of control is to find a secondary method of control suitable for combining with SSVEP.

Recommendations for future work following on from the research in this chapter are summarised here. From the SSVEP experiment outlined in section 5.1:

- Future experiments could investigate SSVEP stimulus of higher frequencies, for user comfort, and with a higher duty cycle for improved amplitude response.
- The comparative study of EEG measuring platforms would be widened to incorporate a larger of devices. The three platforms chosen for the experiment in this chapter were chosen as they were the only ones available at the time.
- For investigating amplitude control in BCMI further experimentation could also investigate a^{max} as well as a^{min} values and subjects ability to control amplitude with this range. The use of real-time feedback is likely to be of importance here.

- Finally, it seems likely that both that speed and accuracy can be improved with more electrodes placed over the visual cortex. A future area of research could be to investigate whether an optimum number of dry electrodes could match or improve on the SSVEP accuracy recorded with the wet electrodes. This would benefit applications for music where dry electrodes are more preferable due to their ease of use and recorded faster response times.

Chapter 6: Investigating affective states as a passive control method for BCMI

This chapter steps away from the SSVEP based BCMI and investigates an area of passive control, which could potentially be combined with SSVEP to expand the musical control on offer in a BCMI. The chapter opens with a review of the role of emotions and music, and the application of affective responses reflected in passive EEG patterns.

Two new affective BCMIs are presented in this chapter. The first, the Affective Jukebox*, forms the basis of a user study to help validate the EEG method of determining levels of affect as represented by music. The second system follows on from this in the shape of a multi-user BCMI performance piece, The Space Between Us, where the affective states of a performer and audience member are approximated to direct the arrangement of a musical piece with strong emotional connotations. The data from a performance of* The Space Between Us *is discussed in this chapter demonstrating the creative potential of combining real-time measures of affect and music generation.*

6.1 Introduction

This chapter takes a step away from the SSVEP method and investigates emotional cues registered in EEG as a passive method of BCMI control. Now that a robust, reliable and accurate method of SSVEP control has been implemented in a BCMI the aim of this area of the research is to find a suitable secondary method of control for integration with an SSVEP BCMI to develop hybrid control over two simultaneous dimensions. As previously explained BCI control can be separated into two discrete categories of user intention. Active control methods provide explicit control over user selection across a limited range of choices, whereas passive control pertains to implicit measurement, where brainwaves are associated with approximations of a user's mental state without any conscious control on the part of the user (George and Le´cuyer 2010, Guger, Edlinger et al. 2011). This chapter outlines significant developments into the detection and use of affective states (emotional approximates) as a control signal in BCMI systems. The work presented in this chapter focuses on the application of BCI methods to new ways of unconsciously controlling music and exploring musical interactions between more than one participant based on affect.

Passive control in a brain-computer music interface (BCMI) provides a means for approximating mental states that can be mapped to select musical phrases, creating a system for real-time musical neuro-feedback. This chapter presents two BCMI systems, the first, a pilot proof-of-concept system titled the Affective Jukebox, is designed to determine the success of music selection based on corresponding affective states measured in EEG. Based on the success of experiments of this first system a second BCMI is presented. This system measures the affective states of two users, a performer and an audience member, during a live musical performance of the piece, The Space Between Us. The system adapts to the affective states of the users and selects sequences of a pre-

composed musical score. By affect-matching music to mood and subsequently plotting affective musical trajectories across a 2-dimensional model of affect, the system attempts to measure the affective interactions of the users, derived from arousal and valence recorded in EEG. The Affective Jukebox validates the method used to read emotions across 2-dimensions in EEG in response to music. Results from a live performance of The Space Between Us indicate that measures of arousal may be controllable by music as a result of neuro-feedback, and that measures of valence are less responsive to musical stimuli, across both users. As such an affective BCMI presents a novel platform for designing individualised musical performance and composition tools where the selection of music can reflect and induce affect in users. Furthermore, a an affective channel of communication shows potential for enhancing collaboration in music making in a wider context, for example in the roles of therapist and patient (Rolvsjord 2004).

6.2 Emotions, music and EEG

Drawing on the motivation to look beyond SSVEP for suitable EEG detection methods that can be utilised for control this chapter focuses on a particular area of passive control. Subconscious control provides a more straight-forward method for integration with active control as it requires less demands of a user. Combining methods of control is considered in the next stage of this research project and its applications are presented in chapter 7. Passive control over music presents an interesting approach to sonifying brain activity as a novel means of understanding complex and difficult to interpret data from EEG in a new light (Baier, Hermann et al. 2007), with some applications moving towards improving medical symptoms (Strehl, Leins et al. 2006). A major benefit of passive control in BCMIs is that a user is free from the distractions of active control that might otherwise occupy the users thoughts and detract from the listening experience. One of the drawbacks of passive control is that the *feeling* of control can diminish when the cognitive tasks, used in active control, are removed.

One of the most exciting areas of detecting unconscious brain states is the field of interpreting emotional states within EEG. Although still a relatively new area of research previous studies have demonstrated the suitability of EEG in attempting to detect both a user's emotional, (often referred to as affective), state (Chanel, Kronegg et al. 2006) as well their emotional response to music (Lin, Wang et al. 2010). One system was piloted, the *Affective Jukebox*, that provides automated music selection by means of emotion detection from EEG. The results confirm our hypothesis that EEG could reliably be used to determine a listeners affective state and control a music selection and playback system with this information in real-time. Emotional control for music making appears to be a natural combination due to the emotional associations inherent with music for many listeners. This link is exemplified by recent studies on affective algorithmic music

composition systems (Williams, Kirke et al. 2014) alongside research that indicates a strong link between the use of emotionally charged music and improvements in cognitive performance (Franco, Swaine et al. 2014). However, studies where emotion recognition in BCI is utilised can be difficult to quantify if success is measured against intention. This challenge increases, as responses to music can often be unpredictable. These factors highlight a need for experimentation with real-time systems for rapid feedback against a set of carefully selected stimuli.

To explore this hypothesis away from the laboratory environment and in a more appropriate musical setting the research reported in this chapter culminates in the presentation of a multi-brain affective-BCMI (further referred to as the *a*-BCMI), for live recital of the piece *The Space Between Us. The Space Between Us* presents an artistic step towards how brainwaves may be harnessed to promote shared, affective, and embodied experiences between performer and audience. The approach used to mapping measures of EEG to music provides a platform for designing performance systems that respond in real-time to the affective states of participants. The objective of the piece is two-fold; to determine whether affective measures in EEG can be influenced by music in an *a*-BCMI system, and to provide an artistic interpretation of the emotional trajectories of participants in a live performance setting. A particular area of interest is the nature of interaction between users and whether such a system can adapt to their affective responses. The *a*-BCMI system monitors the affective states of one performer and one audience member and uses this to select sections of a pre-composed musical score, which is then performed with deliberate emotional connotations as specified by the a-BCMI readings. The multi-brain system provides a novel approach to reflect the user's affective state through music using music as a stimulus to further influence users' states as part of a live performance. The system aims to move the affective states of two users closer

together, creating a shared emotional experience through the music that is based on the emotional measures extracted from the EEG.

6.2.1 Defining Emotion in Music

Music psychology typically documents three types of emotional responses to music: emotion, affect, and mood (Russell and Barrett 1999). These can be considered as the reaction to sudden changes of musical expression, the perception and induced feeling of the emotional tone of music, and a longer lasting emotional association that can be revisited with memory (Lamont and Eerola 2011). Scherer proposes a design-feature model in an attempt to differentiate between emotions and feelings defining *utilitarian emotions* as relatively brief periods of synchronised response to the evaluation of an external or internal event, both liable to rapid change and highly susceptible to musical elicitation (Scherer 2004).

Individuality presents an unpredictable and important influence on listener's emotional response to music. There is a need for experimentation with real-time systems using rapid feedback against a set of carefully selected stimuli to develop systems that are tailored to the individual. Responses will differ from person to person depending on a range of factors such as cultural and social interpretations, preferences, prior experience, memory and so forth. An individual's emotional response to the same piece of music may vary according to factors such as the time of day, fatigue, or other dynamic variables. Additionally, it has been recognised that in the field of music and emotion investigations with social approaches (research involving interactions and shared experiences) is receiving less attention than research based on individual interactions with music (Lamont and Eerola 2011).

Russell's circumplex model of affect (Russell 1980) provides a way of parameterising emotional responses to musical stimuli in two dimensions: valence (positivity) and

arousal (energy or activation), as shown in Figure 33. This model can be mapped together with Hevner's adjective cycle (Henver 1936) to create a dimensional-categorical model that has been widely corroborated by other studies of music and emotion across 2-dimensions (Friberg, Breson et al. 2006, Bradley and Lang 2007). Furthermore the 2D model is well documented with respect to music in terms of neurophysiological measurement by means of EEG (Schmidt and Trainor 2001, Tenke and Kayser 2005, Ramirez and Vamvakousis 2012). Russell's model ties in well with Scherer's definitions of *utilitarian emotions,* which are responses (not reactions) to music that include anger, sadness, happiness, fear, excited and desperation. These responses can be considered as brief moods of high emotional intensity that are susceptible to change from stimuli. It is the effect of music on these moods that we wish to explore, and an approach is taken to compose musical sequences that reflect the emotional connotations of an affective state to induce such moods and enforce them over the duration of a sequence. In the system we present EEG is measured across the final periods of musical sequences to determine whether this has been achieved.

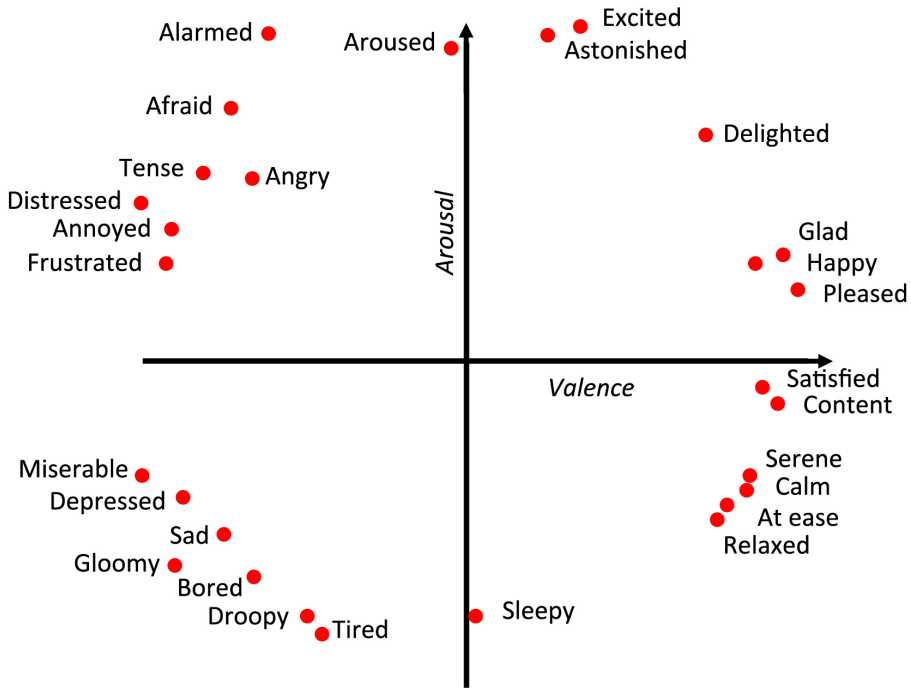

Figure 33. Russell's circumplex model of affect. Adapted from Russell (1980, p1168). Adjectives have been scaled in two dimensions, with valence on the horizontal axis and arousal on the vertical axis.

For the *a*-BCMI system we divide the circumplex model into quadrants which are then indexed via a Cartesian co-ordinate such that 12 discrete co-ordinates can be referenced corresponding to individual affective states across a range of arousal (*a1* – *a6*) and with positive or negative valence (*v-1 or v1)*, as shown in Figure 34. 2 axis give four quadrants, each of which is sub-divided by 3 referring to give 12 affective states. 12 adjectives were selected from the circumplex model such that 'basic' emotions (*sad*, *calm, angry,* and *happy)* are positioned such that adjectives for lower and higher arousal levels can be spaced as evenly as possible from these basic descriptors. In this manner, a co-ordinate of (v-1, a1) would refer to *tired.* Two adjectives from Hevner's list were deliberately avoided in the selection process: *Sleepy* and *aroused,* as they were both placed near to the center of the circumplex model of affect (shown in Figure 33) and might therefore be considered ambiguous as to their valence despite a clear differentiation in arousal level between the

two. There is no reason why additional adjectives could not be incorporated in the future to this model, providing they are scaled appropriately from a categorical model.

The main emotions (*sad*, *calm, angry,* and *happy)* can all be seen in the second and fifth levels (v-1, a2), (v1, a2), (v-1, a5), and (v1, a5) respectively. An emotional trajectory moving from *pleased,* via *happy,* to *excited,* can be represented by a vector which gradually increases in arousal whilst maintaining positive valence: (v1, a4), (v1, a5), (v1, a6).

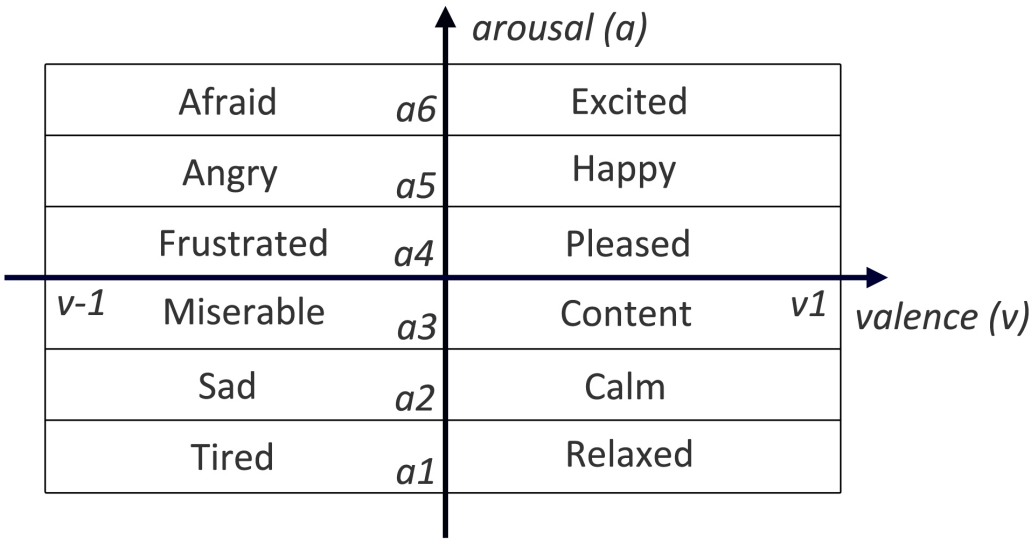

Figure 34. Quadrants with 12 discrete affective adjectives from the circumplex model (afraid, angry, frustrated, excited, happy, pleased, tired, sad, miserable, relaxed, calm, and content).

6.2.2 Perceived vs. Induced Emotions

When designing affective-led systems it is important to recognise the distinction between the perceived emotions of a piece of music (i.e. when a listener reports that it "sounds happy") and music's ability to induce an emotional state within a listener (i.e. when a listener reports that it makes them "feel happy"). These two states are not necessarily linked by the same emotion and are not necessarily interdependent, one can exist without the other. For example a listener may understand the sad tone of a composition, but remain entirely unmoved by it. In the same manner it is not uncommon for a piece of

music to evoke strong emotions in one person, whilst leaving another person feeling cold, even though both listeners may be able to translate the intended emotion of the composition. A further phenomena associated to music listening is the way listeners use music with a strong emotional association to reinforce positive moods of an opposite affective state. This is particularly apparent in studies that monitor the pleasing effects of listening to sad music which has been shown to improve mood (Vuoskoski and Thompson 2012) (Salimpoor, Benovoy et al. 2009). This notion of mood enhancement is also acknowledged in studies that highlight the importance of affect-matching music to mood, to help improve cognitive performance (Franco, Swaine et al. 2014). Although improving cognitive performance is not a primary concern within our research this idea of affect-matching presents an ideal gateway towards engaging or locking-in the listener's affective mood with music before altering their state through the use of an affective trajectory.

An *a*-BCMI system relies on the ability of music to induce an associated affective state. As affective states in response to music are dynamic in nature (as discussed above, they may differ depending on abstract circumstances and may change significantly over time), a system must adapt to the listener accordingly in order to be successful. Therefore the *a*-BCMI we present is designed to match the mood of a user and then update the music being played in response to changes in the mood of the user. This is the approach undertaken in the *Affective Jukebox*. For *The Space Between Us* the system monitors whether a user can subconsciously affect-match themselves to the changes in music related to trajectories across the model in 31. An *a*-BCMI that applies neuro-feedback to manipulate user's affective states during performance provides an interesting model for designing specific emotionally targeted performances. Furthermore, a live performance setting provides a visual realm for communicating emotions whereas monitoring EEG responses provides a separate measure as to whether the intended affective state is actually being induced by either the performer, listener or both.

6.3 The *Affective Jukebox:* Confirming EEG measures with user self-assessment

In order to determine whether the EEG affective model was accurate, a perceptual pilot study was undertaken during May 2014 whereby listeners were invited to self-report their emotional response to music selected autonomically in direct response to the EEG correlations.

Musical mood classification is a growing field in the realm of musical information retrieval, with various possibilities for stimulus selection including systems that utilise machine learning, crowd-sourcing, and acoustic analysis (Knobloch and Zillmann 2002, Hu and Downie 2010, Davis, Allen et al. 2011). In this case, the stimulus set was selected from music which had already been tagged with emotional descriptors by crowd-sourcing in the *Stereomood* project, an "emotional on-line radio that provides music that best suits users' mood and activities" (Cambria, Hussain et al. 2011). The stimuli included material from a range of genres, with a variety of tempos and instrumentation. Material with tags that correspond to the affective adjectives shown in Figure 34 was edited to 30-second clips and subjected to loudness equalisation in order to create the stimulus set shown in Table 14. There was, however, potential for some bias in the crowd-sourced metadata of the musical stimuli. For example, a search for *afraid* yielded *Non, je ne regrette rien* as performed by Edith Piaf. Knowing the lyrical content and delivery of this song, it seemed reasonable to assume that some of the crowd involved in tagging this stimulus did so as *afraid* as they felt that this song might give them the opposite i.e. *courage*. Four sources for each stimulus were initially short-listed, as a mechanism for elimination of erroneously tagged material was required. Therefore, these short-listed stimuli were evaluated in a short perceptual scaling study where listeners were asked to confirm how much they

agreed with each of the crowd-sourced tags. Only stimuli with the largest amount of universal agreement to their documented correlation were progressed (>66% agreement with a standard deviation <0.20).

Stimulus number / Cartesian co-ordinate	**Corresponding affective adjective**	**Musical stimulus (Title, performer)**
1. (a1, v1)	*Tired*	*Dissociation EP*, Gelatinous
2. (a2, v1)	*Sad*	*One day I'll fly away*, Keith Jarret & Charlie Haden
3. (a3,v1)	*Miserable*	*Fade into you*, Chelsea Burgin
4. (a4, v1)	*Frustrated*	*What Kind of Girl*, Kid Moxie
5. (a5, v1)	*Angry*	*Sneak Chamber*, Tsutchie & Force of Nature
6. (a6, v1)	*Afraid*	*Perfect Drug*, Nine Inch Nails
7. (a1, v2)	*Relaxed*	*I'll take the road*, Dave Reachill
8. (a2, v2)	*Calm*	*Jung Greezy*, Snake Oil
9. (a3, v2)	*Content*	*Get Lucky*, Daft Punk
10. (a4, v2)	*Pleased*	*All around*, Tahiti 80
11. (a5, v2)	*Happy*	*Theo*, Apples
12. (a6, v2)	*Excited*	*Tropp'Cazz'Pa'Capa*, Smania Uagliuns

Table 14. Stimulus set used in evaluation study. Cartesian co-ordinates for arousal and valence are determined by EEG analysis. The corresponding affective adjective is then used to select a musical stimulus.

6.3.1 Listening panel and experimental procedure

Six listeners participated in the study. Each participant had some experience of critical listening. All participants were male, aged between 22-35. The study was conducted via a Max/MSP graphical user interface. Listening tests were conducted via full range loudspeakers in a quiet room with dry acoustics. Participants were allowed to adjust volume levels according to their own preference during a familiarisation exercise. Instead of integrating an external library of stimuli, such as the Affective Digitized Sounds database (IADS) of audio stimuli for emotion induction (Bradley and Lang 2007) the affective jukebox system was calibrated using excerpts from the full stimulus set in order to ensure that the EEG recordings were directly relevant to the stimulus set.

6.3.2 Familiarisation and calibration stage

The familiarisation exercise allowed listeners to hear the following stimuli in order to calibrate the EEG response: tired (v1, a1), relaxed (v2, a1), afraid (v1, a6), and excited (v2, a6), meaning that listeners had experienced one stimulus from each quadrant at the maximal and minimal arousal levels before undertaking the procedure. Arousal and valence (AV) levels were recorded to determine the maximum and minimum levels on a participant-by-participant basis. These values were used to normalise the individual's responses in the main study.

6.3.3 Main study

After an initial measure of a user's resting affective state to select the first musical clip, the self-report/listening task was repeated over a series of trials, (Figure 35). EEG is collected from the last 10 seconds of each listening session (where each listening session lasts for the length of one complete stimulus) and the corresponding affective co-ordinate is used to select the next clip.

Once playback of the selected stimulus has finished, listeners are asked to scale their agreement with the intended emotion:

"Thinking about the music you just heard would you agree that it reflected the way you felt whilst the previous piece of music was playing (or in the first test, before any music was playing at) all?"

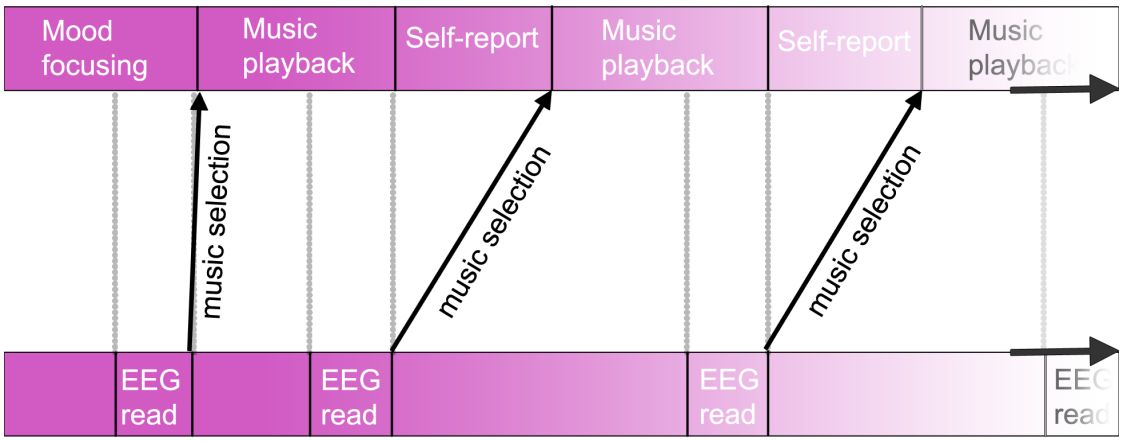

Figure 35. Design of the *Affective Jukebox* paradigm. A staggered method of selection based playback and self-reporting was used over trials for each participant.

In response, listeners were presented with a slider using a hidden 100-point scale with end points marked "totally agree" to "totally disagree". It is acknowledged that in repeatedly answering this question users were required to recall previous responses to music in every instance, which is by no means an easy feat, but is necessary in order to reflect the paradigm of a jukebox playback system. Each study was conducted twice, the first in order to acquaint the participant with the study paradigm (Figure 35) and user interface. Data was only recorded and analysed from the second run of each participant, in order to ensure that participants understood the task.

6.3.4 Results

Listener responses were analysed in the SPSS package. Mean agreement across all participants was 0.85 with a standard deviation of 0.14 and a standard error of mean of

0.07, as shown in Table 15. Although only a limited number of listeners took part in the evaluation, mean agreement was relatively high suggesting that there was a good degree of corroboration between the EEG measurement and the mood meta-tagging that was used to select the stimuli. However, the overall standard deviation (σ) was also quite high. The low sample size implies that an improvement in the margin of error could be achieved by using a larger number of participants for such an evaluation in future – to improve the σ to a confidence level of > 92% (α=<0.07) would mean at least halving the margin of error, requiring quadruple the number of participants (to achieve a confidence level of > 95% would require ~ 8 times the number of participants). The relatively low standard error of mean suggests that this hypothesis might be borne out by a larger scale evaluation, but such testing was beyond the scope of this pilot study.

Mean	Std. Deviation (σ)	Std. Error of Mean	Variance
0.85	0.14	0.07	2.14

Table 15. Mean agreement, standard deviation, standard error of mean, and variance across all participants (shown to 2 decimal places).

The mean agreement and standard deviation across each individual participant, as shown in Table 16, was then examined. Although mean agreement was good, the individual participants' standard deviation remained high with α=>0.05 in all participants, and particularly high standard deviation in two participants (participant 2 and 5).

Participant number	Mean	Std. Deviation (σ)
1	0.90	0.06
2	0.79	0.25
3	0.88	0.11
4	0.77	0.14
5	0.90	0.12
6	0.85	0.13

Table 16. Mean agreement and standard deviation from each individual participant (shown to 2 decimal places).

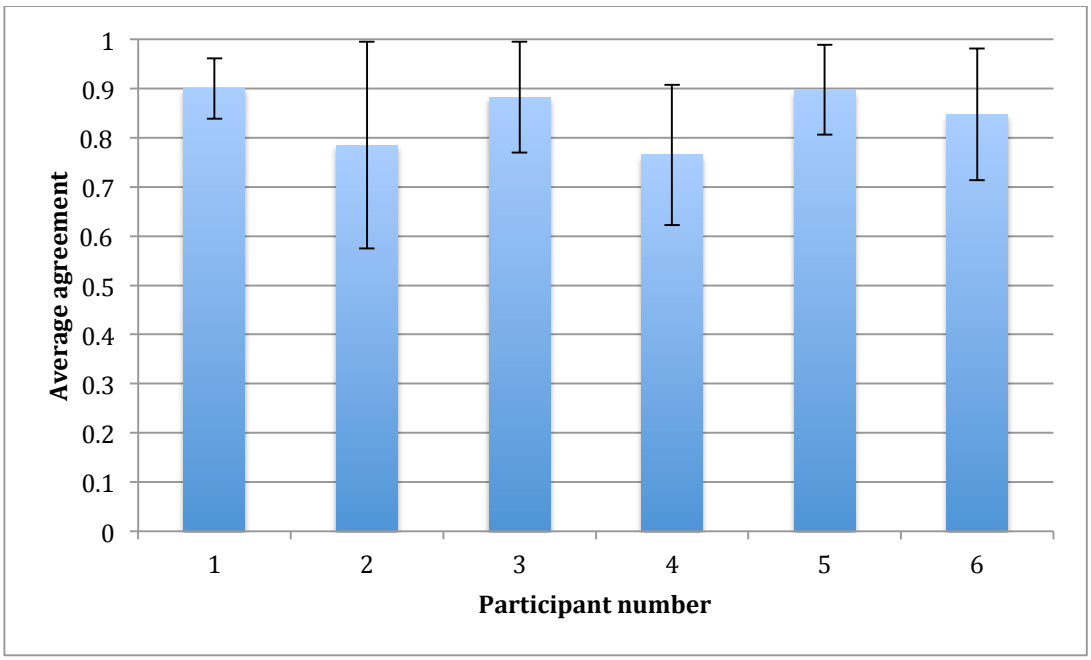

Figure 36. Mean agreement across individual participants with standard deviation shown in error bars. Note that the participants with the highest mean agreement also exhibit the lowest standard deviation in their responses.

Three participants (participants 1, 3, and 5) had additional training in EEG use and showed both a higher mean agreement and lower standard deviation in their responses, as shown in Figure 36, than the three participants who had not previously been trained in

the system (participant number 2 and 4). However, there was only a relatively small variation in standard deviation between participants 3-6, regardless of previous training. This suggests that a robust evaluation of a training system might be useful in further work to determine whether any significant improvement in mean agreement and can be generated in previously untrained participants.

6.3.4 Discussion

This section examines the performance of the system, it's limitations and observations during trials.

6.3.4.1 Performance and limitations

It is important to acknowledge that this was a pilot study using only a limited panel of participants of similar age and gender. The small number of musical stimuli was specified in order to reduce unmanageable variations in listener responses, however an improved system could increase the number of stimuli tailored to the individual; and thereby increase the performance of the system.

Moreover the tests highlighted that individual musical preferences, even within this small subset of possible users, caused a wide variation of responses. However, we hypothesise that within these caveats the system should be scalable to larger numbers of users.

One possible method to tackle the problem of individual musical preferences would be to carry out a pre-screening exercise (for example the STOMP system (Rentfrow and Gosling 2003)) to improve the affective resolution by reducing individual bias to specific genres. Similarly a wider pool of musical stimuli could be used to address this.

6.3.4.2 Observations

Whilst evaluating the study, a particular neurofeedback loop was observed. Listeners tended to select the same clip of music repeatedly once they had reached a settled affective state. This suggests an intuitive affective state, which is perhaps to be expected. When a listener actively engages with music that reflects their mood, their mood is unlikely to change for a period of time as they enjoy the listening experience associated to their affective state. Over time it could be seen that valence decreased after repeated exposure to the same clip. It is easy to imagine becoming annoyed after listening to the same 30 seconds repeatedly. Anecdotally, most users readily understood the corresponding states of stimuli in the extremes of the arousal dimension, but this would require a more rigorous evaluation to confirm.

It was also noted that listeners with more training found it possible to *actively* select different music clips, a function which would make an interesting focus for future work. This may hold potential for future applications with active control, such as selecting music to improve mood or to aid relaxation.

6.4 The Space Between Us

To recap, *The Space Between Us* is designed to explore two main enquiries. Firstly, whether affective measurements in EEG respond to pre-composed music in both a performer and a listener during live performance, determining whether plotting affective trajectories across the model in Figure 34 can regulate the detected affective states induced during the performance in a neuro-feedback derived process. The second is to monitor the affective interactions between two users during music making to help determine whether future BCMI systems can be built to adapt to this interaction in the future. Collaboration between people is a highly regarded feature of musical participation and an affective channel of communication that adapts to users offers an exciting prospect in designing BCMI systems for a variety of uses, outside of performance. One example is in BCMI systems for interaction between therapist and patient.

The piece was composed during the Summer of 2014 for grand piano, live electronics (controlled by the pianist) and voice. Before the performance begins the singer and an audience member are each fitted with a brain cap to measure EEG simultaneously throughout the performance. The system records their mood at the end each window, as outlined above, and maps this to discrete pre-composed musical sequences (essentially, small chunks of score), which are then in turn performed. The system is synchronized to a global clock that acts as both a loose visual metronome and to trigger the event of a new score selection at the end of each window (1 window = 90 seconds). The clock is presented as a counter alongside the score to the singer and the pianist on-stage. Depending on the measured arousal valence response of the two subjects, a variety of affective trajectories can be plotted across the 2D grid (Figure 34). The system displays the corresponding score whilst monitoring changes in arousal and valence at the end of each window. EEG data is also written to a text file for off-line analysis post-performance.

6.4.1 Structure

The music of the piece contains twelve pre-composed musical sections. Each section is composed using specific musical features with affective correlations as emotional cues. Essentially it is the sequencing of the sections that is led by the affective states, with the intention that the final section of each window will subsequently influence the affective state as measured from the performer and the audience member at the end of the current section (Figure 37). For the final 20 seconds of each window both the performer and audience member are instructed to remain physically still, to reduce interference in measuring EEG, and reflect on the mood that the current music and performance has instilled in them. A prompt is provided to the singer on-screen using prominent colour changes that both warns the viewer when this process occurs, and displays the timing of this period.

The piece, although performed continuously, comprises three movements (following a randomly selected preliminary window). Each movement is four windows long and is designed to elicit three separate things. The first movement attempts firstly to affect-match the mood of the singer by selecting a score from their response to the randomly selected musical score of the preliminary window, and then shift their mood across three adjacent affective states. The second movement performs the same task for the audience member using their response to the last window of movement one for initial affect-matching, and the third movement selects the first window based on a median average of both subject's affective state and plots a trajectory in an attempt to both move their state's simultaneously and towards each other across the 2D space. This overall success of these aims is evaluated against EEG data and discussed further on.

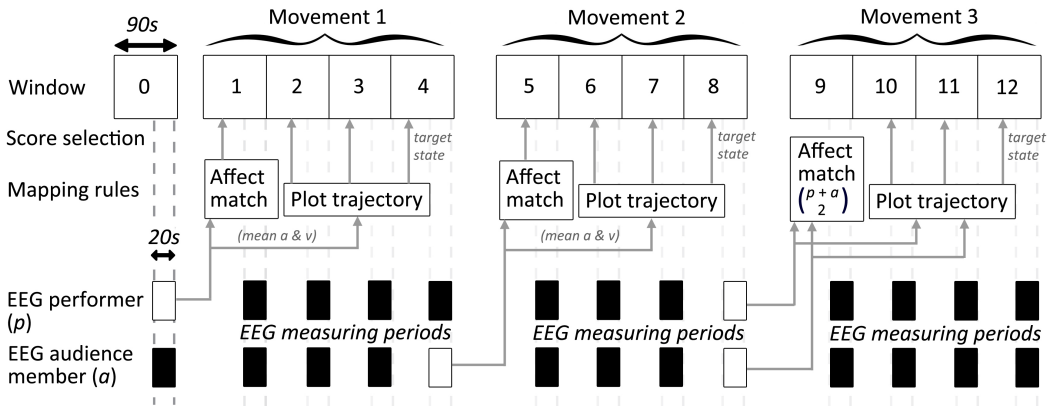

Figure 37. Structure of *The Space Between Us.* EEG measuring periods occur during the last 20 seconds of each window. The measures of mean arousal and valence taken indicated by white boxes are used by the rules of the mapping algorithm to select score sections and to plot trajectories.

The score for movement 1, window 0 is selected at random and the resulting 2D coordinate (x = *v*, y = *a*) recorded at the end of the window is saved as the initial state. The corresponding score of this state is selected for window 1. A target coordinate is determined by randomly selecting a state that is three steps away across the plane, either (±1v, ± 2a) or (±3a). Multiplying the target co-ordinate by 0.33, 0.66 and 1 respectively sets a trajectory across the next three windows. Associated states are selected that span the projected path and select the corresponding musical phrase from the array. Movement 2 then follows a similar procedure, however the system takes into account the affective response of only the audience member. The mapping for movement 3 uses the coordinates of each subject from the fourth window of movement 2 as initial values, *p* (performer) and *a* (audience member). The difference between each individuals' emotional state, as shown in equation 3, becomes the target value for movement 3's fourth window, again with multiplication factors for the preceding three windows, plotting a trajectory. The final window in movement 3 selects a target value of positive valence, at the closest state to the difference between *p* and *a* to induce a positive emotional ending to the performance experience.

$$\sum \frac{p+a}{2} \qquad (3)$$

Whereas the first and second movements aim to affect-match and then shift the mood of the singer and audience member respectively, the third movement aspires to shift the mood of both parties across the same trajectory, together. Although EEG is being measured from both users throughout the entire performance the intention was to design and test a mapping system where the participants did not feel pressurized or need to take responsibility for the outcome of the system.

It was necessary to determine trajectory paths in advance so that both performers could be warned of the upcoming score for many of the windows in advance. In the same way that musicians read ahead when sight-reading this helps prepare for changes and allows for smooth transitions between windows, and as such this is an implementation challenge which may be unique to the field of real-time BCMI. Additionally, the effect of repetitive score selection due to an affect-matching feedback loop, as observed in the *Affective Jukebox* study outlined above, can be minimized by this approach.

An illustrative video of a performance and rehearsal session of the premiere in Berlin, Germany December 2014, is included in Appendix 1.

6.4.2 System design

The multi-user *a*-BCMI system is built around two EEG systems with identical that include brain caps, electrodes, hardware and software. The signal flow of the EEG processing is outlined in Figure 38. Equipment was selected to be portable and facilitate comfortable participation. A wireless EEG setup was used which allowed for physical separation from the PCs used to receive and process EEG data, a practical necessity in the live performance environment. The performer was required to move freely during periods when EEG was not being detected, and it was important for the participating audience member to feel as

though they are an extension of the system, without feeling distracted or overwhelmed by the equipment in their vicinity.

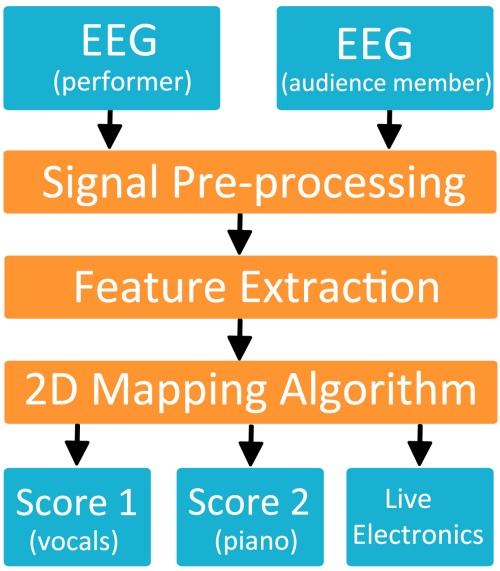

Figure 38. Signal flow of the EEG as input to the control functions in the *a*-BCMI. The 2D mapping algorithm selects musical sequences, which are presented as a score, depending on different rules during performance. The system either selects a target state and corresponding score to match the arousal and valence of a user or it determines a target states by calculating the mean values of both user's arousal measures.

Two laptop PCs are used on-stage to allow both performers to see the scores of their respective parts, as illustrated in Figure 39. A third laptop PC is situated off-stage next to the audience member. A closed wireless local area network (WLAN) allowed for data transfer across all three PCs for EEG processing, score selection, and clock synchronization.

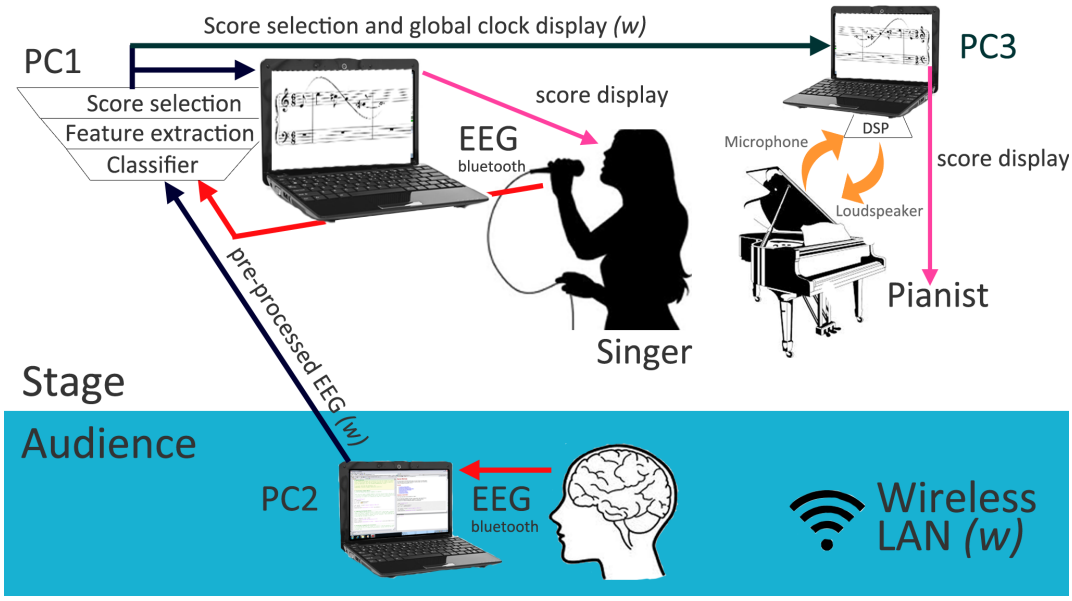

Figure 39. Signal-flow, connectivity and the layout of the main components in the multi-brain *a*-BCMI system used in *The Space Between Us.*

6.4.2.1 System Components

- **EEG measuring (Singer and audience member brain caps)**. EEG signals are measured with active g.tec Sahara electrodes, a g.tec Sahara amplifier and a gMOBILAB+ digitizer. Data is sent via Bluetooth to PC1 and PC2 for the performer and audience member respectively. Active electrodes require no gel application and are therefore more straightforward and quicker to setup than wetware systems. The active g.tec Sahara electrodes each house 8 pins designed to penetrate through hair and achieve a good connection with the scalp, further reducing system impedance.
- **3 laptop PCs.** There are three interconnected PCs in the system, each designed to perform a different role related to its primary user. PC1 is positioned on-stage in front of the singer and placed on a music stand. The computer firstly pre-processes raw EEG data from the singer's brain cap in Matlab Simulink. This combines with the audience member's pre-processed EEG data wirelessly received from PC2. EEG

data classification and feature extraction for both users is performed by Simulink running on PC1 then the scaled output values are sent to a mapping algorithm in Pure Data for score selection from Simulink via a bespoke *s*-function that converts data into the Open Sound Control (OSC) protocol to be sent internally via the User Datagram Protocol UDP. The master Pure Data patch on PC1 manages the global clock, maps affective features to the score selection and through the visual extension GEM, displays the score for the singer. PC2 receives raw EEG from the audience member's brain cap. Again, EEG is captured by Simulink and sent wirelessly via OSC to PC1. Global controls are housed in a third Pure Data patch to allow an engineer to start (and also to stop and reset if problems arise) the performance at will. The global commands are sent wirelessly, again via OSC and received by the master patch in PC1. PC3 performs two functions, to display the score and the clock to the pianist and to handle the real-time audio digital signal processing (DSP) of the piano, outlined under the bullet point below. The first function is achieved by a third Pure Data patch that receives clock updates and score selection commands, wirelessly from the master patch in PC1. These commands are passed to a GEM window in PC3, to display the score and clock to the pianist. The second function is realised through a real-time audio processing feedback loop.

- **Processed piano feedback loop**. A condenser microphone captures the sound from inside the body of the piano which is fed, using an external soundcard, into a MAX/MSP patch hosted on PC3. The bespoke patch feeds the audio through a series of effects processors; spectral freeze, sample and hold, and a delay line; and then passes it back out via the soundcard to a loudspeaker placed underneath the body of the grand piano, facing upwards so as to resonate the strings. The pianist, using the faders and buttons of a USB digital control surface connected to PC3,

manually controls the parameters of the audio effects, mixing them together in real-time according to instructions marked in the score. The result produces sustained ethereal characteristics that provide a subtle blend with the acoustic sound of the piano when fed back into the resonant body of the instrument. The effects are used predominantly for music phrases with negative valence and/or low arousal, where there is minimal rhythmic activity, atonal harmonic structures and drone-like sustain, specifically the states *Relaxed, Frustrated,* and *Angry*.

6.4.3. Musical Composition

The piece is composed to attempt to trigger physiological changes in EEG on an unconscious affective level, and also to clearly communicate the intended emotions through the music, lyrical content and the delivery of the performance. Ultimately if an audience struggles with interpreting the emotional cues in the music, then the other two aspects are designed to help aid this emotional communication. When previous studies have investigated EEG emotional correlates in response to music the focus has often been more biased towards measuring success solely within EEG data, rather than on the suitability of musical stimuli (Daly, Malik et al. 2014). Also little has been done to study the effects of musical performance on affective correlates in EEG, though the affective potential of multimodal stimuli has been well documented (Lipscomb 1999, Camurri, Volpe et al. 2005). As such, factors such as stage demeanor, delivery and lyrical content were considered useful in order to help explore this area and investigate their combined effects. To assist with this, the lyrical content for the piece was edited from copyright-free works of Percy Bysshe Shelley, an English romantic poet well regarded for the strong emotions his writing evokes.

Two of the most widely accepted musical parameters that influence arousal and valence are respectively, tempo and mode (Dillman Carpentier and Potter 2007, van der Zwaag,

Westerink et al. 2011). Franco et. al (Franco, Swaine et al. 2014) identify further expressive cues in music related to mood, such as *happy*: harmonic consonance and off-beat accentuation, and *angry*: harmonic dissonance and a greater density of note onsets. Additionally, the KTH performance rules provide a set of relative values for arousal and valence linked to musical performance attributes (Friberg, Breson et al. 2006). However, as the authors also recognize, it is extremely difficult to compose music according to rules based on 30-40 specific musical parameters, especially when trying to impart a coherent musical style. It was also felt important that the composition of *The Space Between Us* to feel intrinsically human, therefore computer-aided composition techniques, which could have abided by such strict rule-sets, were avoided. With this in mind the KTH rules were used as a guide to help apply emotional characteristics with a particular focus on global functions such as mode, tonality, rhythmic density, intensity and dynamics, and with attention paid to attributes of shorter durations such as articulation, phrase arch and punctuation, which contain ranges with particular emotionally expressive qualities.

Twelve parts to the piece were composed in-line with the twelve states categorised in the affective model. Global musical features were mapped across the axes of the two dimensions depending on their affective association. For example, rhythmic intensity increased from *Tired/Relaxed* to *Afraid/Excited*, according to an emotional interpretation as opposed to a strict mathematical scaling. It was felt that applying a straightforward major/minor mode distinction between all positive and negative states of valence would provide too much obvious contrast and restrict the pieces interest and overall unity, so an atonal style (music of no fixed central tonality) was used in a number of negative valence states, which provided a useful range of dissonance. Furthermore, extended and experimental performance techniques were utilised to reinforce stark changes in emotion, as well as the piano feedback digital effects routines. For example, certain parts required the piano strings to be played aggressively inside of the body using a plectrum (*Frustrated*,

Angry), and some parts required a strongly affected vocal style to help convey different intensities of emotion (*Miserable*, *Frustrated*). The composition was developed through workshop sessions with the singer, in order to cultivate an individualised stimulus set that they could connect with and feel comfortable delivering, according to the required emotional expressivity.

It would not be practical to provide the full score here, however, a brief look at the musical score from two parts provides an insight into some elements of the compositional design. Figure 40 shows the score for *Tired*, which is associated with minimal arousal and negative valence. The musical term *calando* instructs performers that the pace slows down throughout, whilst simultaneously quieting, an effect designed to mimic the notion of falling asleep. To reinforce this the piano part is a series of descending cadences constructed on a series of atonal harmonic transitions and their variations. This is then matched by a short vocal line which comes in after the piano, once the mood has been set. Both performers are instructed to perform the part with a decreasing energy which is to be perceived physically as well as aurally. The lyrics here reflect the evocation of a memory, which is often the case during the period of tiredness before sleep.

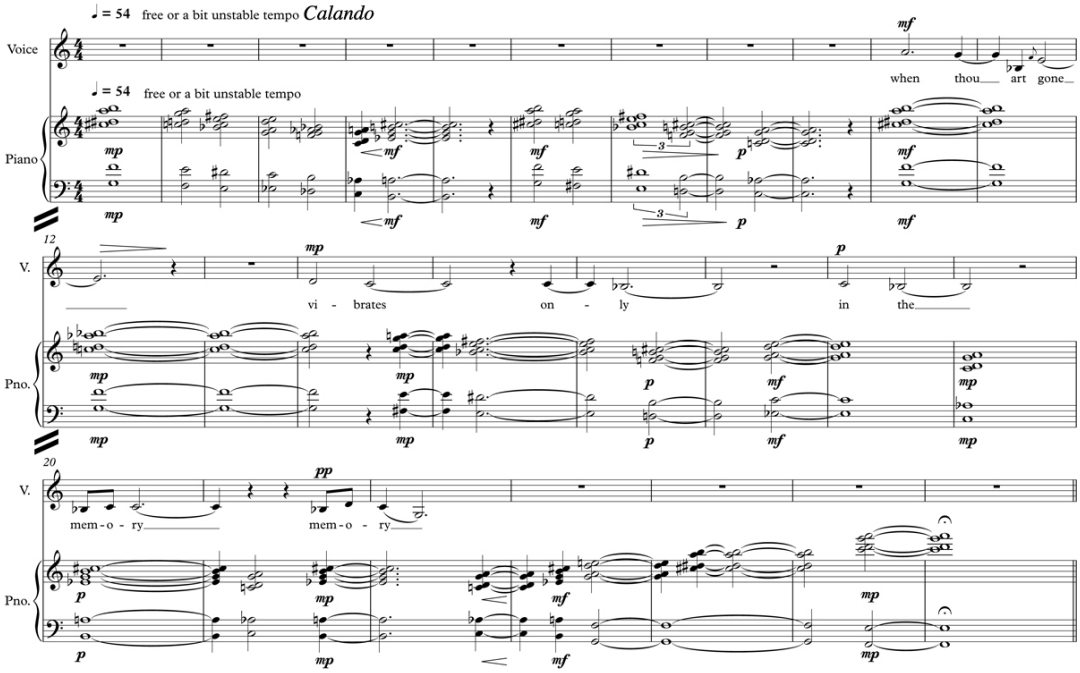

Figure 40. The vocal and piano score for *Tired.* The piano part contains a series descending atonal harmonic transitions. The vocal line descends in pitch with the piano over a series of long, sustained notes as both parts slow down irregularly in tempo.

Figure 41 presents the first section of the score for *Excited*, which is at the opposite end of the affective model from *Tired*, with maximal arousal and positive valence. The score illustrates a fast tempo in 4/4 timing with a repetitive, regular piano-led beat and high rhythmic density. The notes are played in an almost staccato style, short and sharp, a technique mirrored by the vocal part to express fast bursts of energy. In the latter stages of this section dynamic changes are introduced alongside different rhythmic patterns (triplets and then 7/4) to maintain listener engagement with high arousal without relying on excessive repetition.

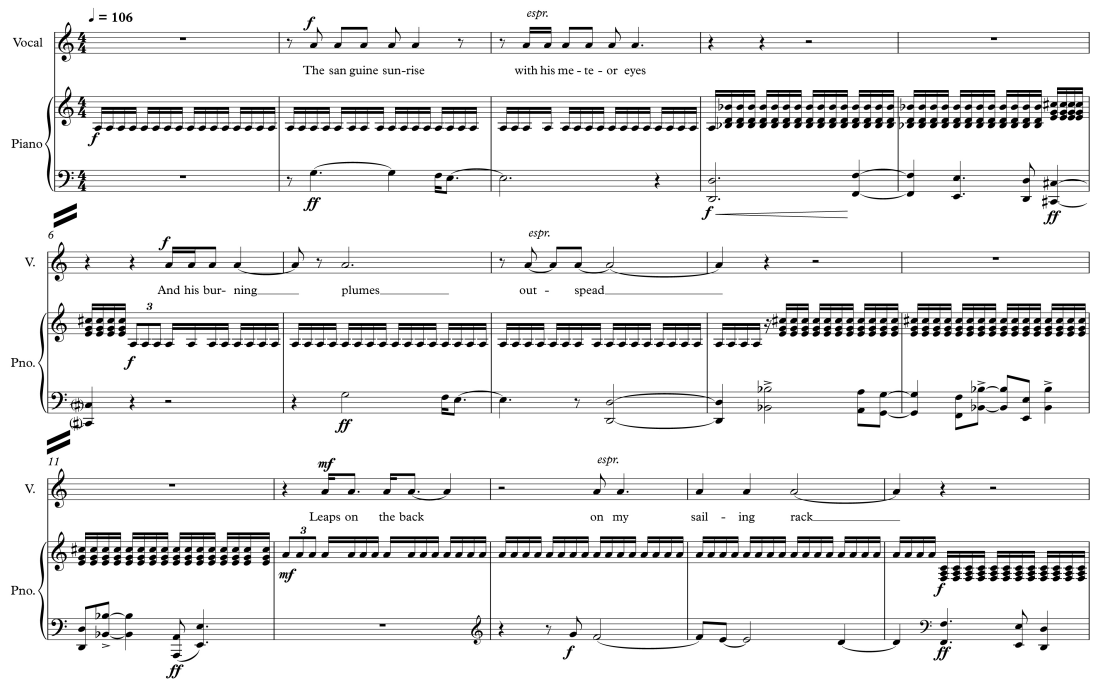

Figure 41. The first half of the vocal and piano score for *Excited.* The piano part leads with a regular 4/4 rhythm with minimal harmonic variation. The vocal part sings the lyrics to the same pitch with a mixture of staccato and the occasional sustained note. The tempo is much faster than the score for *Tired* for a more energetic delivery.

The lyrics for *Excited* are adapted from Shelley's stanzas *The Cloud*, a playful poem about the never-ending cycle of life. The poem is written from the perspective of an electrically charged cloud eliciting strong, colourful and exciting visual imagery. Three parts were selected not to contain a vocal line, in order to present the associated state and to provide some variation within the performance. *Relaxed, Happy* and *Afraid* contained only a piano line and/or electronic feedback.

6.4.4 Performance and observations

Data collected during the premier performance of *The Space Between Us* (Figure 42), shown in Table 17, provides an interesting account of the measured arousal and valence in the EEG of the performer and audience participant. Quantitative valence and arousal values were determined from an earlier training period where user response was classified against the stimulus set. Statistical significance would require multiple iterations

of the performance or a larger number of *a*-BCMI users in one performance. This presents two problems. Firstly, the practical demands, including the costs, of hosting either of these scenarios is outside the feasibility of our resources. Secondly, we predict that there would be large variations in data between events, even with the same users, based on the commonplace variation in affective states discussed in the introduction of this chapter. Measures of affective states are not definitive and it would appear logical to expect that the responses from both individuals are likely to change depending on a near infinite range of external factors that might influence their mood resulting in a different global arrangement of the music sections upon every performance. It is therefore important to reiterate that this system and the associated performance were designed specifically for a singular experience for the participants. As such the data presented in this section is merely indicative of the potential for a multi-user *a*-BCMI system and should be read with this in mind.

Figure 42. Photo of a live performance of the *Space Between Us.* At the 9th Conference on Interdisciplinary Musicology, December 2014, Berlin, Germany.

Window	Affect-matched state	System trajectory (**bold** = target state)	Changes in score AV measures	User 1 Arousal	User 1 Valence	User 1 trajectory	User 2 Arousal	User 2 Valence	User 2 trajectory
0		Tired (randomly selected)		1.65	-0.1		1.54	0.23	
1	Sad		(a=inc)	1.85	0.43	(a=inc), (v=inc)	1.59	0.28	(a=inc)
2		Miserable	(a=inc)	1.82	0.44	(a=dec)	1.45	-0.09	(a=dec),(v=dec)
3		Frustrated	(a=inc)	1.86	0.55	(a=inc)	1.48	0.18	(a=inc)
4		**Angry**	(a=inc)	1.92	0.48	(a=inc)	1.66	0.11	(a=inc)
5	Afraid		(a=inc)	1.72	0.58	(a=dec)	1.54	-0.18	(a=dec)
6		Afraid	constant	1.62	0.21	(a=dec)	1.52	0.2	(a=dec)
7		Excited	(v=inc)	2.23	0.44	(a=inc)	1.65	0.31	(a=inc)
8		**Happy**	(a=dec)	1.84	0.46	(a=dec)	1.66	0.25	(a=inc)
9	Miserable (Happy)		(v=dec), (a=dec)	1.58	0.4	(a=dec)	1.75	0.24	(a=dec)

10		Pleased	(a=inc), (v=inc)	1.77	0.62	(a=inc)	1.73	0.2	(a=dec)
11		Happy	(a=inc)	1.96	0.42	(a=inc)	1.55	0.19	(a=dec)
12		**Excited**	(a=inc)	1.68	0.31	(a=dec)	1.79	0.22	(a=inc)

Table 17. System trajectory, score selection and user EEG data for a performance of *The Space Between Us*. User 1 is the singer and User 2 is the audience member. The correlation between musical stimuli and affective measures from EEG can be seen in the changes across each user's affective measures (User 1 and User 2 trajectory columns) against the trajectories of the music (column heading 'Changes in score AV'). Increments (inc) and decrements (dec) are used for labelling as the system is calibrated slightly differently to the response of each user.

Table 17 shows arousal and valence from both users, alongside the selected scores and the system's affective trajectories. Useful comparisons can be made with the arousal/valence trajectories against the musical trajectories. At the beginning of each movement the system attempts to affect-match the music (in windows 1, 5 and 9) to the corresponding user's response to the music of the previous window (window 1 = user 1, window 5 = user 2, window 3 = mean of user 1 and user 2). The mapping algorithm in the master Pure Data patch plots a global affective trajectory and the responses of both users are recorded. The results indicate a strong link with the musical trajectories and changes in user arousal. Changes in valence are noted as the difference between negative and positive values whereas ranges of arousal are scaled according to a calibration task undertaken during a rehearsal prior to performance.

The affect-matching of the system at the beginning of each window shows a clear pattern of user's affective states closely matching the music of the previous window. Movement 1 begins with *Sad*, which is taken from the affective response of the singer at the end of *Tired*. *Sad* and *Tired* sit next to each other in the 2D model. Similarly at the end of movement 1 user 2's response selects Afraid, which is close to the previous window's *Angry* music. Finally the system takes an approximate measure of both users' affective response of window 8, *Happy*. The mean of the two measures pre-empts a repeat of *Happy* (as indicated in brackets in Table 17) but the system follows an in-built rule to avoid repetition of states and shifts the score selection by a random measure of up to two steps across the 2D space.

The data in Table 17 shows that valence in both users generally stays positive throughout, and does therefore not appear to be strongly linked to changes in the music. This could be the result of either the composition lacking enough negative musical features although another explanation could be that this is an indication of the levels of mental engagement required of both the performer and the audience member in an intense concert

environment. This suggests that investigations of arousal are perhaps more telling of the affective experiences of both parties. Significantly, across both users measures of arousal move upwards or downwards in the direction of the target state in each movement, even with occasional deviation. This suggests a substantial success of the system and the performance in the ability to move user arousal across a trajectory.

A number of anomalies exist in the data, which are perhaps to be expected when analysing a performance of this kind. In particular the affective responses of the audience member have less correlation with the musical trajectories than those of the singer. In light of the fact that the composition was developed during workshop sessions with the singer (where EEG was also monitored), this might be expected, as the music became individualised to the singer during these sessions. The audience member had no previous exposure to any of the music and is perhaps likely to have less emotional attachment towards, and also less emotional understanding of the piece. Other incongruences in the data may be the result of musical factors. For example, in the first movement, window 2, the performance of *Miserable* induces negative changes in arousal against the previous *Sad* section. This may be indicative of the music either reinforcing negative emotions or even that *Miserable* feels less energised than *Sad*. The sections are both quite similar in musical terms, both with a slow tempo and in an atonal key. It is interesting that this drop in arousal occurs in both users. Another interesting outcome can be seen in windows 5 and 6, where measures of arousal drop across both users. A system error allowed *Afraid* to be played twice in a row during windows 5 and 6 (the rule avoiding repetition failed to avert this). Interestingly, this allows us to see the effect of prolonged music against all the other shorter sections. Here, measures of arousal decrease across both windows. This could perhaps be because of two possibilities. Firstly, there is no vocal part during *Afraid*. The piano attempts to use tonal relationships to convey the feeling of *Afraid*, but there is far less drama than in the atonal and vocally shouted *Angry*, which precedes *Afraid.* Secondly, as already mentioned,

arousal has been known to decrease with repeated exposure to the same stimuli. The exact same part being performed twice may well have contributed to this. A further observation is in the role of the physical demands of performing which are likely to play a significant role in the singer's overall levels of arousal and valence. Taking other bio-signal measures of arousal taken from the singer are likely to corroborate arousal measures in EEG readings as they are more closely linked to physical exertion. For example, using an ECG/EKG, a faster heart rate is likely to be caused by singing high-intensity phrases which place a greater demand on the cardio-vascular system.

There are a number of limitations with active BCI control for music making. Two in particular are particularly relevant to music-making activities. The first is the amount of time between cognitive processing and the corresponding control signal being detected, and the variability of this time. The second is a lack of simultaneous controls on offer. Both of these attributes, which are analogous (and typically related in BCMI) to real-time musical response and the musical notion of polyphony, are intrinsic to the design of interactive digital musical interfaces (Hunt and Kirk 2000). In response to the need for more complex control is a shift towards combining active control with secondary, *passive* brainwave detection methods (Zander, Kothe et al. 2009, Eaton and Miranda 2014) to create *hybrid* BCI control. The motivation for investigating measures of passive control in EEG stems from this school-of-thought: I wanted to develop BCMIs that offer deeper and more complex control than active systems alone, combining passive and active methods to create novel BCMIs. However, before this could be fully realised I was keen to explore the potential of passive control alone, and the research outlined in this chapter focuses on detecting passive measures related to emotions with EEG, for control over music in a BCMI system.

6.5 Conclusions

Passive BCI systems are not always limited to the restraints of active control methods and present an interesting partnership for music systems whereby mental states detected from EEG can be mapped to music generation, in particular affective BCMIs. Neuro-feedback allows for individualised music in a BCMI to be selected in response to measures of affect which addresses the problem of users being different from one another and how measures of affect can alter at different times.

This chapter presents a passive system which reads emotions in 2-dimension. The metrics were validated in a pilot study that used self-report to corroborate the EEG metrics in an affective jukebox. For *The Space Between Us*, the aim was to see how two people could have a musical interaction using passive EEG control to detect affective states.

The pilot study suggests that it is possible for a jukebox style affective music playback system to be controlled via EEG. Listener self-report confirmed that there was a good deal of corroboration between the EEG co-ordinates and individual affective state whilst engaging with the music selections. Both the affective jukebox system and the experimental methodology are in a pilot stage but these early results are promising and suggest that this is an appropriate methodology to employ when conducting further study with a larger number of participants and more complicated EEG derived affective correlations. Possible future applications using this approach might include a more advanced affective jukebox taking into account personal music preferences, affectively driven composition engines and performance systems.

The piece, *The Space Between Us,* shows that affect can be measured during musical performance. Early results suggest that some interesting control over arousal was achieved through neuro-feedback, whereas measures of valence were less conclusive. The

system has constraints which are practical in order to be used in a real-world context, away from laboratory conditions. A minimal electrode setup is used alongside a rudimentary approach to classifying measures of affect in real-time.

6.6 Summary

This chapter illustrates how detecting affective states in EEG presents a useful approach for passively controlling music. The use of music with emotional connotations within a neurofeedback loops adds a particularly interesting element for monitoring music-making processes.

A pilot study to confirm the hypothesis that affective responses to music EEG can be determined was conducted. The results indicate that a musical jukebox driven by affective states could be realised. The need for attention to individualised musical stimuli was observed. This formed the basis of *The Space Between Us*, where a multi-brain BCMI system was realised that provided the driver for selecting pre-composed music based on affective responses of a performer and an audience member. This is the second demonstration of a multi-brain BCMI (after *Activating Memory*), addressing **RQ2**. In this example a shared implicit musical experience is created where the BCMI used adapts to the responses of both users.

Both the methods of affect-matching and plotting affective trajectories during active listening and musical performance demonstrate a novel and creative approach to mapping. Here, EEG data detected across two dimensions is mapped to associated music and these techniques contribute towards addressing **RQ4**.

For *The Space Between Us* the BCMI system is presented in a different manner than with the previous SSVEP systems. Brain-control is implied and as far as the audience is concerned provides a background like feature to the performance, which is drawn into view only through the appearance of the brain cap on the singer and on an audience member in the front row. The removal of active control for all participants provides a more open arena for music engagement without distraction, and although control is only

implied there is no evidence to indicate that a user's connection to the music is any less. In fact the question of how connected a user feels to the music generated from either active or passive control presents a very interesting area for future investigation.

Finally, affective states are potentially useful in combination with SSVEP, in a hybrid BCMI, for two reasons. Firstly, the technique requires no further initiative from the user and as such it would not detract from the role of SSVEP gazing and subsequent control. Secondly, a two-dimensional model of control could be added to four channels of SSVEP control, providing deeper and more complex combinations for mappings. This finding and subsequent investigations documented further on contribute towards addressing **RQ5**.

Chapter 7: The hybrid brain-computer music interface

This chapter is the culmination of both the developments made in improving the SSVEP method and explorations in measuring affective responses to music covered within the previous three chapters. The body of work presented in this chapter brings together the robustness of the SSVEP method and the creative potential of expanding user control with affective response alongside a third method of user control, motor imagery via event-related desynchronisation.

Two systems that express the creative possibilities of combining EEG control methods, known as hybrid BCMIs, are outlined in this chapter. The first, joyBeat*, is a drum machine with a step sequencer controlled by both SSVEP and affective response. The second BCMI used for the performance piece,* A Stark Mind*, expands on* joyBeat *with the addition of a third control method, motor imagery, to create a live audiovisual performance that aims to create not only a three dimensional hybrid BCMI, but an immersive performance that communicates BCMI to an audience in an engaging and effective way.*

7.1 Introduction

As the final research chapter in the thesis, the work presented here is the coming together of the topics explored earlier on in this thesis and the culmination of the ideas developed in the previous BCMIs towards addressing the research questions outlined in chapter 1. Each of the BCMIs exhibited previously throughout this thesis stands on its own, exploring a specific area for a creative purpose, but also they all represent steps towards the final two BCMIs in this chapter. That said, although the two BCMIs in this chapter represent the achievement of certain goals they do not represent the end of this BCMI research, they do not signify a final page in the field of creativity and control within BCMI, far from it. They are designed, as each of the previous systems have also been, to be improved, expanded upon and used as stepping stones towards future BCMIs that further push the boundaries of brainwave control and artistic creativity. The only difference here is that the future research beyond this chapter will not form part of this doctoral project and remains entirely open to others to do so.

The two hybrid BCMI systems in this chapter are designed to illustrate applications of musical creativity in their approaches towards control, musicality and performance. And both exhibit a slightly freer level of artistic freedom than the previous BCMIs as their focus caters more towards developing for a musician and the audience or listener's appreciation of BCMI respectively, than for a particular research-led objective, such as corroborating a hypothesis (*Affective Jukebox* or *The Space Between Us*), or for a specific user or development goal (*Activating Memory*). This is largely because the technical groundwork has previously been laid through the successes of the previous BCMIs, and the technologies are adapted for the uses of the two new BCMIs here. The successful integration of control methods is the only practical scientific goal realised in these

systems, therefore the success of musical control through the mappings has no other bounds.

That said there are still three key factors of the research of hybrid BCMIs in this chapter that go towards addressing **RQ1**, **RQ2**, and **RQ5**. The first is the implementation of a hybrid BCMI, a proof-of-concept system following on from the study in to affective responses in EEG, outlined in chapter 5. This prototype aims to see whether combining both SSVEP and affective response is feasible in a hybrid BCMI. Furthermore it aims to investigate how mappings from both inputs can be used effectively in a musical application. The second factor is the ability to integrate a second method of active control into the prototype system towards a performance based BCMI. Again, how mappings can be used effectively from both a user experience and a musical perspective requires consideration here. The third factor is the development of a live performance around the hybrid BCMI that utilises a strong and artistic visual element that both enhances the visual aspects of BCMI performance and also provides a visual cue to an audience of how brainwave control is being relayed into music.

joybeat is a hybrid BCMI prototype built in late 2014 that integrates both SSVEP and affective measures as inputs for controlling a software based drum machine and step sequencer. The control methods are separated so that the active control offered by SSVEP stimuli provides note ON/OFF control for creating unique rhythmic patterns to suit the user. The secondary, and passive method of control alters the sonic characteristic of the drum sounds, musically reflecting changes in affective measures. This broadens both the user's interactions with the interface, especially through the passive feedback loop added to SSVEP control, as well as the musical outcomes of the system.

A second hybrid BCMI was developed during early 2015 for the performance piece *A Stark Mind* that brings together a third method of brainwave control. Motor imagery, the

detection of imagined physical movements, presents itself as a useful technique as it is an active control method that requires no external stimuli, as extra stimuli could interfere with or add too much complexity in conjunction with the flickering SSVEP icons. *A Stark Mind* attempts to improve on BCMI performance through an extra, immersive visual element designed to help bridge the link between a BCMI user's control and the resulting music. This is for the benefit of the audience rather than the benefit of the BCMI user.

7.2.1 The hybrid BCMI

In the hybrid BCI examples discussed in section 2.1.10 two control methods were successfully detected in the same system, although a secondary method was used to reinforce the accuracy of a primary and control over both dimensions did not occur simultaneously. However, this is an innovative approach for improving the accuracy of one method, by incorporating a second, and would be useful in a BCMI where accuracy is poor, for example in the *Flex* BCMI (chapter 4) where the EEG device is known to produce low quality EEG. The SSVEP experiment presented in chapter 5 confirms high levels of control accuracy for platforms 1 and 2 and these provide acceptable levels for integrating the technique in music making applications. In this context, when combining the SSVEP method with one or more secondary methods of control there is not such a need to use the secondary methods to reinforce the primary as accuracy is already high. Plus, when using a passive secondary method of control it is unlikely that accuracy will be improved anyway. As such any secondary methods can be treated as standalone methods of control and can be creatively exploited for additional musical mappings. The nature of the secondary methods needs to be carefully considered, especially in the pursuit of simultaneous control as, for example, generating simultaneous mental patterns may prove difficult for a user and the ability to detect their responses is not well documented.

For a BCMI a suitable secondary control method is one that does not rely on external stimuli, as this can be an added distraction to a user, especially when the primary control method employs

external stimuli. It can become dangerous to add control complexity into musical interface design for it's own sake, as the extra attention and concentration required can detract a user from the enjoyment of the listening experience, and it remains to be seen where the balance between providing enough control to keep a user engaged and providing too much control that the experience becomes overwhelming or un-enjoyable lies. In a practical sense this should be determined by the objectives of the particular BCMI. Creating control-difficulty also creates an opportunity for reward and the ability to achieve some level of expertise, a common notion in music. On the other hand, in a music therapy setting for example, obscuring an easily accessible route to being able to play the interface quickly and easily make put users off from carrying on. Furthermore, if all or a significant amount of a user's time and concentration is being lent to the tasks of control then the acts of musical engagement and listening for entertainment become in danger of being overlooked, even to the point of disappearing. This is an important consideration to bear in mind when expanding control in BCMI systems and contributed to the decision to incorporate a method of passive control, as no extra conscious effort from a user is required. As the two systems presented in later sections of this chapter were designed with advances of control in mind, they both (in particular *A Stark Mind*) require a high level of mental effort to control, is illustrative of the complexity on offer, and could have also been designed for a wide range of other mental demands. A user requires a high level of concentration during performance to control the interface in the intended ways. Applications for other objectives may wish to simplify the hybrid control on offer to provide some respite for a user.

The first hybrid BCMI system presented in this chapter, *joyBeat,* demonstrates the combination of both SSVEP and affective state detection. With this notion of user experience in mind a secondary active control method was selected, not based on accuracy or reliability, but on its suitability for use alongside SSVEP and affective state detection during music making. The second part of this chapter presents *A Stark Mind,* the final BCMI system and composition of

this thesis. *A Stark Mind* attempts to address a number of the issues raised throughout this thesis regarding performing with brainwaves. In particular accuracy, live performance, communicating control to an audience in an interesting and artistic way. Furthermore, *A Stark Mind* demonstrates that three methods of brainwave detection can be used to control a live musical performance simultaneously in an innovative and creative manner.

7.2 joyBeat

The *joyBeat* BCMI maps SSVEP control and affective states across parameters of a software based drum machine. A drum machine, combined with a step-sequencer, is one of the most commonly recognised tools in electronic music. The ability to program drum patterns on the fly and affect the sound characteristics of the drums was first introduced in the early electronic drum machines of the 1980's. For example Roland's[18] TR-909, perhaps the most iconic of drum machines, has helped define entire genres of music, including techno, hip-hop and house. Still popular today, sequencing patterns and manipulating sounds with drums machines is a staple skill for both hardware and software implementations.

joyBeat is the first example in this thesis of a BCMI for controlling an existing, well-known music tool. The SSVEP method is suitable for actively creating patterns, via selecting steps within a sequence that can be sequenced together. In previous BCMIs so far only four SSVEP choices have been available. A sequencer is defined by its resolution, which is the number of steps in the sequence, which can be associated with the number of rhythmic beats in a bar. A phrase with only four steps is particularly limiting, even when different instruments are layered together. To provide control over eight steps, therefore doubling the size of the available patterns, *joyBeat* uses two SSVEP stimuli units, thus providing eight SSVEP channels. As shown in the experiment conducted in chapter 5 control over more channels can be poorer across a selected, best performing few. For *joyBeat* the user's response was tested against a wider bandwidth of frequencies for selecting those with the better response times.

Control over the drums in *joyBeat* is extended with passive affective state detection.

[18] http://www.rolandus.com/

Changes in affective states during run-time alter the sonic characteristics of the drums creating a primitive method of providing auditory feedback on a user's EEG changes across the arousal/valence plane. Although this method of secondary control here is not explicit the extra dimension on offer from affective response is useful for two things; enhancing the musical qualities and widening control.

7.2.1 System design

The *joybeat* BCMI employs the same SSVEP detection method outlined in section 3.2.1 using band-power filters and a linear threshold classifier, with the addition of a second external SSVEP stimuli unit. The hybrid BCMI also integrates the method of detecting affective states, as outlined in section 3.2.2.

Using the EEG measuring hardware of platform 2 the elements of the system can be summarised as:

- **EEG measurement.** g.tec g.Gamma passive wet electrodes and brain cap. Electrodes connect to a g.tec gamma amplifier, which is in turn connects to a g.tec MOBIlab+ digitiser. The EEG signal is sent via Bluetooth to a host laptop PC for processing, classification, visual feedback and sound generation. Platform 1 was chosen for accuracy over speed, as precision over sequencer steps over response time was desired.
- **SSVEP stimuli.** Two external SSVEP stimuli units are combined to provide 8 control channels over the following frequencies: 7Hz, 7.5Hz, 8Hz, 9Hz, 10Hz, 11Hz, 12.5Hz and 13Hz. These frequencies were a best-fit selection over trials across 6 – 14Hz.
- **EEG classification.** SSVEP is derived in real-time using a linear threshold classifier, again as outlined in section 3.2.1. Affective states are measured using

electrodes placed across the frontal cortex to detect arousal and valence. Matlab Simulink processes the EEG in real-time and sends the data out of the program via the OSC protocol.

- **Transformation algorithms.** Processed EEG is transmitted from Matlab to Pure Data to be managed by the transformation algorithm and mapped to both the musical parameters and synchronised with the GUI (developed in Pure Data GEM) for visual feedback. Data is split into two pathways, one for managing the SSVEP detections and one for monitoring the affective data (Figure 43). Data from both pathways is synchronised using quantisation (explained in 7.2.4) to a visual metronome that governs the playback of the sequencer.
- **Feedback.** Feedback is presented visually using a GUI displayed on the host laptop. Here, a visualisation of the step sequencer is displayed to inform the user of previous and current SSVEP selections. Audio feedback is provided through the resultant music generated by synthesis algorithms in Pure Data (discussed further on).

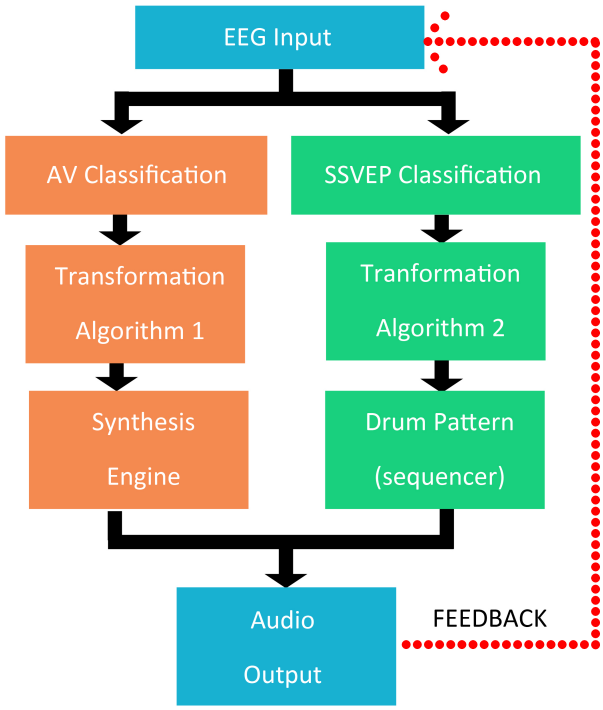

Figure 43. *joyBeat* BCMI data flow and system components**.**

When the sequencer is manually activated (the user selects the Start/Stop button in the GUI, Figure 44) the current position of the step-sequencer moves across the 8 steps in-synchrony with the metronome at a predetermined BPM (beats per minute) value. The current playback step moves across the top row of 8 horizontal boxes, representing the 8 steps of the sequence and two bars of four beats. Figure 44 shows the current step as step 1 as noted by the black square in the first box of the top row. Every 16 bars the system automatically toggles through the four instruments; kick drum, snare drum, closed hi-hat and open high hat. The screenshot in Figure 44 displays the current instrument as the bass drum. To turn drum hits ON/OFF for the current instrument the user gazes at the corresponding icons that represent each step. To select/deselect drum hits for different instruments over the 8 steps the user waits until the instrument selector has automatically moved to the target instrument and then performs SSVEP control. For example, Figure 44 shows the current instrument to be the bass drum. Each of the 8 steps in the sequence can

be assigned a bass drum hit or de-selection during this period. In Figure 44 steps 1 and 5 have associated bass drum hits, whilst the other steps remain empty. Likewise the snare drum has hits in steps 3 and 8, the closed hi-hat in 2, 5 and 8, and the open hi-hat in 4 and 7. Only the current instrument can be controlled using SSVEP irrespective of the current step.

A video of *joybeat* is included in Appendix 1 demonstrating the interface in use and provides an overview of how the GUI relates to user control and the musical outcome.

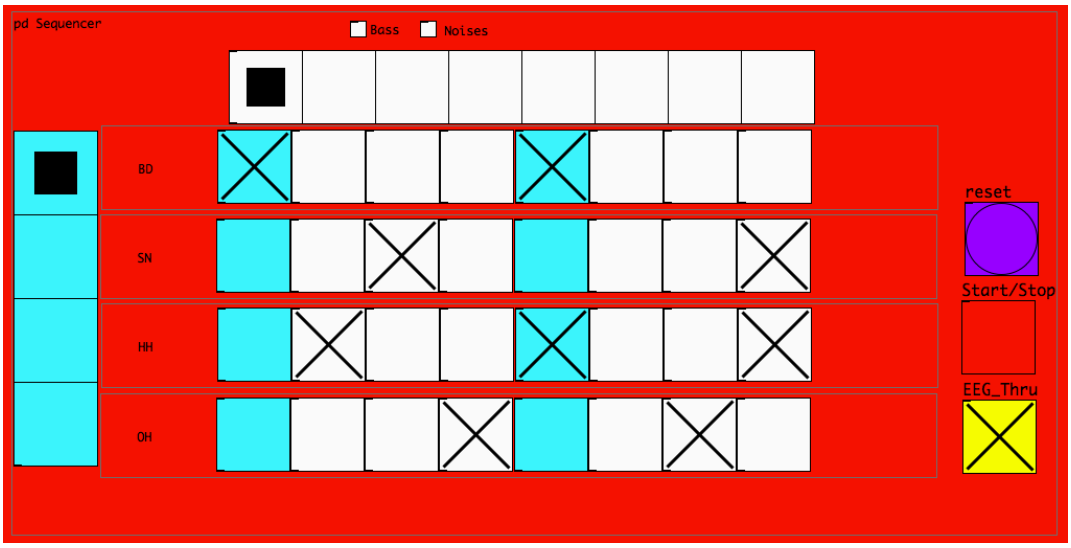

Figure 44: *joyBeat* GUI of step-sequencer showing drum pattern, current step and current voice. The current instrument is indicated by the vertical row of boxes positioned on the left hand side of the GUI, labelled as BD (bass drum), SD (snare drum), HH (hi-hat) and OH (open-hat).

7.2.2 Simultaneous SSVEP and affective state detection 2-dimensional control

The two methods control, SVEP and affective measures, present themselves as particularly suitable to be used together as EEG signals from separate areas of the brain is being influenced and subsequently monitored; the visual cortex located at the lower rear of the head and the frontal cortex located across the upper sides of the forehead. Observations during tests in the development phase suggested there were no notable effects on conflicting frequency bands in the frontal cortex during SSVEP gazing. Given the nature of

passive control here, i.e. there are no mental or physical requirements associated with generating affective responses in this BCMI, it is straightforward to assume that there are no associated EEG side affects that will influence the SSVEP control signal.

7.2.3 Mappings

This section examines both the active and passive control mappings used in *joyBeat.*

7.2.3.1 Active control mappings

As already stated, SSVEP control is mapped to threshold-based switches to match the type of control necessary for toggling drum hits ON and OFF. Once the input signal exceeds the a^{min} threshold the corresponding drum hit is initially turned on. As there is no amplitude control used here a^{min} values can be set high in the range between a^{min} and a^{max}. This reduces the risk of false positive values appearing from the lower part of the range. Further commands toggle the hit OFF, then ON again and so on. This allows for patterns to be changed during playback, and a user can even rectify mistakes and improve patterns thus creating a dynamic drum machine that can be continuously updated during performance. Such an instrument is useful for live music performance as it continuously plays back patterns in time without pauses or interruptions, and is also useful as a composition tool for generating ideas and developing evolving sequences of rhythmic patterns.

7.2.3.2 Passive control mappings

Measures of affect in *joyBeat* contribute to control in a different way than SSVEP detection. AV levels (see chapter 6 for an introduction to AV) are measured and averaged over windows with a length pre-determined by the user. In the default setting AV is normalised and averaged over 6 bar windows. The transformation algorithm compares values against those recorded from the previous window and changes are mapped to musical features

according to mapping rules. The transformation algorithm determines AV levels shortly before the first onset of the 7th bar in order for the parameters to be affected before transients on beat 1 that could cause audible artefacts. An adaptive approach was used to measure states of high and low AV during performance in order to gauge the approximate boundaries of the 2-dimensional space. Each time a boundary was exceeded a new boundary was set. This is not a useful approach for consistently representing AV (or emotional) states but provides a novel method for producing interesting musical results.

AV co-ordinates across the 2-dimensional space are mapped to parameters for four Frequency Modulation (FM) synthesisers (Chowning 1973) and their respective envelopes, each of which provides the sound source for one of the four drum instruments. A synthesis engine programmed in Pure Data responds in synchrony with the metronome (using quantisation) to the values received from the control values that are received from the transformation algorithms. In some cases the parameter settings are determined by small stochastic ranges to provide further variability of spectral effects, to give the effect of an ever-changing feel. In simple terms the mappings of arousal and valence to timbral parameters is outlined in Table 18.

Positive / Negative valence:	
Characteristic	Musical Interpretation
Consonance / dissonance	FM frequency relationships*
Harsh / Smooth	Envelope release times*

Positive / Negative Arousal:	
Characteristic	Musical Interpretation
Fast / Slow	Tempo changes between 4 bar windows from averaging EEG
Alert / Sluggish	Envelope attack times*

Table 18. Arousal and valence mappings to musical parameters in *joyBeat*. Parameters marked with an asterisk are mapped to dynamic stochastic ranges.

7.2.4 Discussion and observations

joyBeat demonstrates a novel application of a hybrid BCMI which uses both active and passive BCI control simultaneously and with no added effort from the user than SSVEP control. The two BCI methods are used separately for mapping input commands to different parameters using a many-to-many mapping approach. The hybrid BCMI gives reliable control over 8 SSVEP frequencies that are attuned to the individual with AV response providing a useful method for secondary control. In the future, more AV mappings could be investigated to explore the range of controls on offer. Also in in the future a comparison between the hybrid systems' many-to-many and the single feature BCMIs' one-to-many mappings could be undertaken.

Initial, exploratory trials have shown that additional users can yield a high level of accuracy in SSVEP control and in creating chosen rhythmic sequences. It was also reported

that the musical results of the AV mappings add a more exciting and unpredictable element to the process, delaying boredom through non-repetitive sounds. In these trials, 3 users were able to reliably control SSVEP across 8 channels (with frequencies selected to suit individual preference) in order to create the desired rhythmic patterns. The users all commented that the system was easy to control and quick to adapt to using, however they all possess in-depth knowledge of drum machine functionality.

Traditional drum machines are useful to musicians as they are instantaneously responsive to inputs. When sequences are being played drum steps can be toggled ON and OFF to alter patterns in real-time. With BCMI control a short delay is to be expected, but this doesn't necessarily affect the musical outcome, which still loops the sequence in time (as shown in the video of *joyBeat* in Appendix 1). As already touched upon, commands from both input channels were quantised to the metronome. Quantisation delays commands so that they appear on the beat so the resulting music is always in time (Desain and Honing 1989). With a fast BPM of 215 (as per the *joyBeat* video in Appendix 1) each step is 279ms apart, and just under this would be the maximum delay time with quantisation. With response times of up to 4 - 5 seconds an extra 279ms is relatively imperceptible. As mentioned in section 7.2.3.2 AV mappings are quantised to take effect every 6 bars. Quantisation is a common technique used in drum machines, and most other music software, to give the illusion of timing precision.

State switching is used with SSVEP to simplify BCMI control. The addition of SSVEP amplitude control could be employed in future iterations. One example of a potential application could be to select a target velocity range for each drum hit, a common function in drum machines. Issues can arise when instruments change and steps of the next instrument are altered when a user wishes to control the previous instrument. A 9th SSVEP input would be useful here to manually change the instrument. Furthermore a third

dimension of BCI control could be used here to switch between or select the different instruments.

Currently, the timbral mapping to affective measures in *joyBeat* is on the whole arbitrary as its use is merely demonstrative of the additional dimension of AV control on offer, and more musical mappings are an obvious area for future exploration. A full evaluation of the performance of the hybrid system, by comparing it against single control systems (including one-to-many mappings) would be useful in future studies. This can also be applied to determine the accuracy of the BCI methods being employed, informing future iterations and alternative mapping strategies.

7.3 A Stark Mind

Unlike the traditional musical notation used for performances of *Activating Memory* the score for *A Stark Mind* consists of colourful, abstract visual patterns. The decision for this was two-fold. Firstly, an abstract score allows for much more varied artistic interpretation, and although the graphics have direct musical connotations that are translated by the musicians, the option for musical variety is much wider, and this sense of freedom can help push the music in new directions, allowing the musicians to work together in new and unpredictable ways making every performance different from the last. Secondly, projecting the score onstage can help draw an audience in closer to the performance and communicates how the hybrid BCMI performer's brainwaves are able to control the score and conduct the musicians at the same time, without having to be able to read musical notation. Appendix 1 contains an unedited video of a performance of *A Stark Mind* at the 11th International Symposium on Computer Music Multidisciplinary Research (CMMR), in June 2015.

Again, the primary method of control in *A Stark Mind* is the SSVEP technique. And like *joyBeat* SSVEP control is expanded to provide 8 input channels by combining two of the SSVEP stimuli units. The SSVEP choices allow the hybrid BCMI performer to select visual patterns and control effects that correspond to different musical phrases and instrumental playing techniques. In addition, there are two other methods of brainwave control in *A Stark Mind*. Motor imagery via ERD, using the method outlined in section 3.2.3, is used to extend SSVEP control. This application of the method is explained in more depth in section 7.3.3.1, but where previous hybrid BCI systems have used a secondary method of active control to reinforce a primary method, here motor imagery creates additional control options when used in parallel with SSVEP control. In the hybrid BCMI arousal and valence are again used to interpret emotional descriptors in EEG, in the method outlined in section

3.2.2. During performances of *A Stark Mind* changes in arousal and valence are mapped to parameters of the visual score to invoke musical changes associated with different affective states. For example, if the hybrid BCMI performer's measure of arousal decreases during one time window of analysis indicating a move towards a state of 'calm', the playback speed of a particular visual pattern will increase by a corresponding amount. This conducts the musicians to play faster during the next time window. This increase in musical tempo has the knock-on effect of increasing the hybrid BCMI performer's arousal, which the system would target as 'excited', and so the mapping of arousal (and also of valence) is used to regulate the affective states of the hybrid BCMI performer during by responding to their affective changes in real-time. This provides a novel approach to using emotional indicators in EEG to control music and also influence affective states in a manner that also adds an element of unpredictability and variance to the live performance.

The integration of three control methods in the hybrid BCMI not only increases the amount of options available for a user but it allows for simultaneous musical control across three EEG dimensions (Figure 45). This simultaneous control provides the BCMI equivalent of musical polyphony, a concept ingrained in many traditional musical interfaces. Combining two methods of active control (SSVEP and motor imagery), coupled with the passive control method of mapping affective responses to music, demonstrates a unique application of how BCMI systems can push the boundaries of creativity in computer music.

7.3.1 Simultaneous 3-D BCMI control via SSVEP, affective state detection and motor imagery

Combining the three methods of control is the central task of the BCMI for *A Stark Mind.* Although the three locations for detecting the three phenomena are in different areas of the brain, it is accepted that there may be overlapping patterns in the regions detected,

especially as similar bandwidths are being measured. Tests with *joyBeat* suggested that SSVEP stimuli did not significantly affect alpha waves within the same bandwidth that were detected across the prefrontal cortex. The method for generating motor imagery again influences waves in the alpha band, but the motor cortex is much closer than to the visual cortex than the frontal cortex. Some artefacts from SSVEP control were detected across the P_3 electrode position. Because of this, this channel was omitted from detecting motor imagery in the hybrid bcMI, to minimise the risk of overlapping interference. An alternative approach to overcome this issue could be to shift the SSVEP stimuli frequency range to the beta range (between 12.5Hz and 30Hz) to avoid artefacts appearing in the alpha range across the motor cortex. In doing this the implications for SSVEP control would need thorough consideration. Future work could also investigate the combined performance of and SSVEP and motor imagery against performing control using each method individually.

There appeared to be no major detrimental effects in SSVEP EEG patterns when motor imagery was conducted in parallel. The only notable observation was the extra cognitive effort required from the user to exert the required control over both parameters.

7.3.2 System design

The transformation algorithms map control data from the three control dimensions to a visual engine (Figure 45), which although is used to conduct the music it replaces the musical engine commonly found in BCMIs. Classification of both SSVEP and motor imagery is synchronised so that positive or negative motor imagery detections are monitored retrospectively during a short time window leading up to positive SSVEP detection; the period associated with icon gazing. Therefore overlapping windows of motor imagery detection are recorded throughout the piece for instantaneous recall. The outcome of this

retrospective measurement affects the SSVEP control one of two ways depending on the detected state.

Again, platform 2 (the g.tec g.Gamma EEG system) is used for live performance, for best SSVEP accuracy. In Matlab the pre-processed signal is split into three pathways, to allow processing of each control method from the relevant electrode channels.

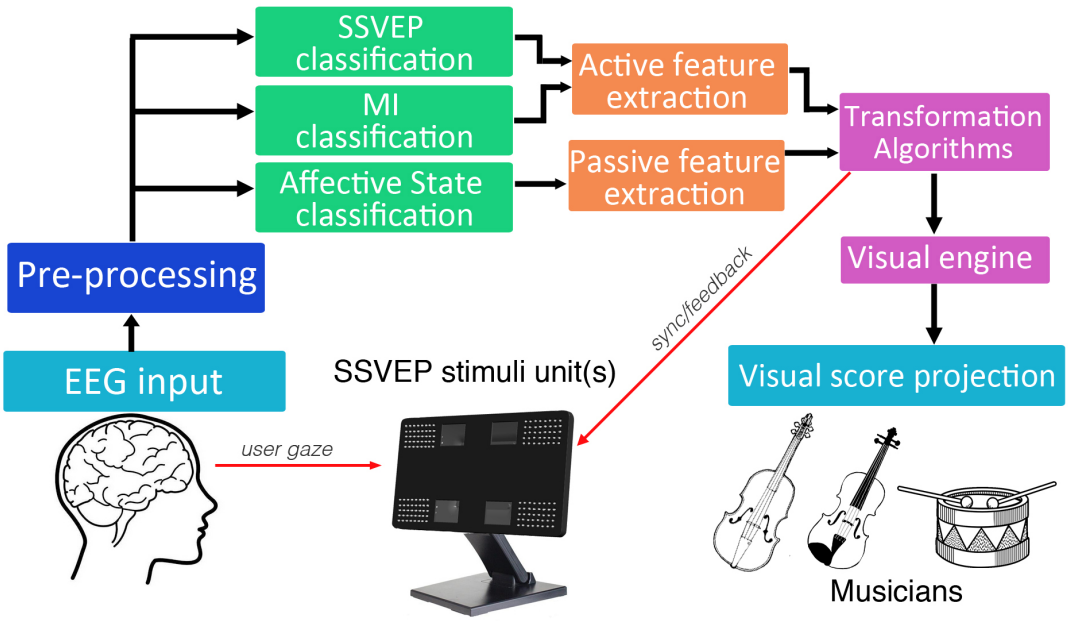

Figure 45. Overview of the BCMI elements and signal flow for *A Stark Mind.*

7.3.3 Mappings

This section examines both the active and passive control mappings used in *A Stark Mind.*

7.3.3.1 Active Control Mappings

Of the two SSVEP units used to provide active control one unit offers four controls for selection of visual patterns and effects synchronised with a global clock. The second unit provides four controls for real-time visual effects control over a range of parameters such as the effect's speed or depth, or the opacity against the non-effected pattern. Unit one

control is mapped to macro arrangement mappings whereas the second unit is mapped to real-time effects control.

The TFT displays are used to communicate the mappings for all 8 combined SSVEP-motor imagery channels for the three sections of *A Stark Mind*. Mappings are displayed as abbreviated text descriptors for simplification during performance, an example of the images presented on the second unit to control effects is shown in Figure 46.

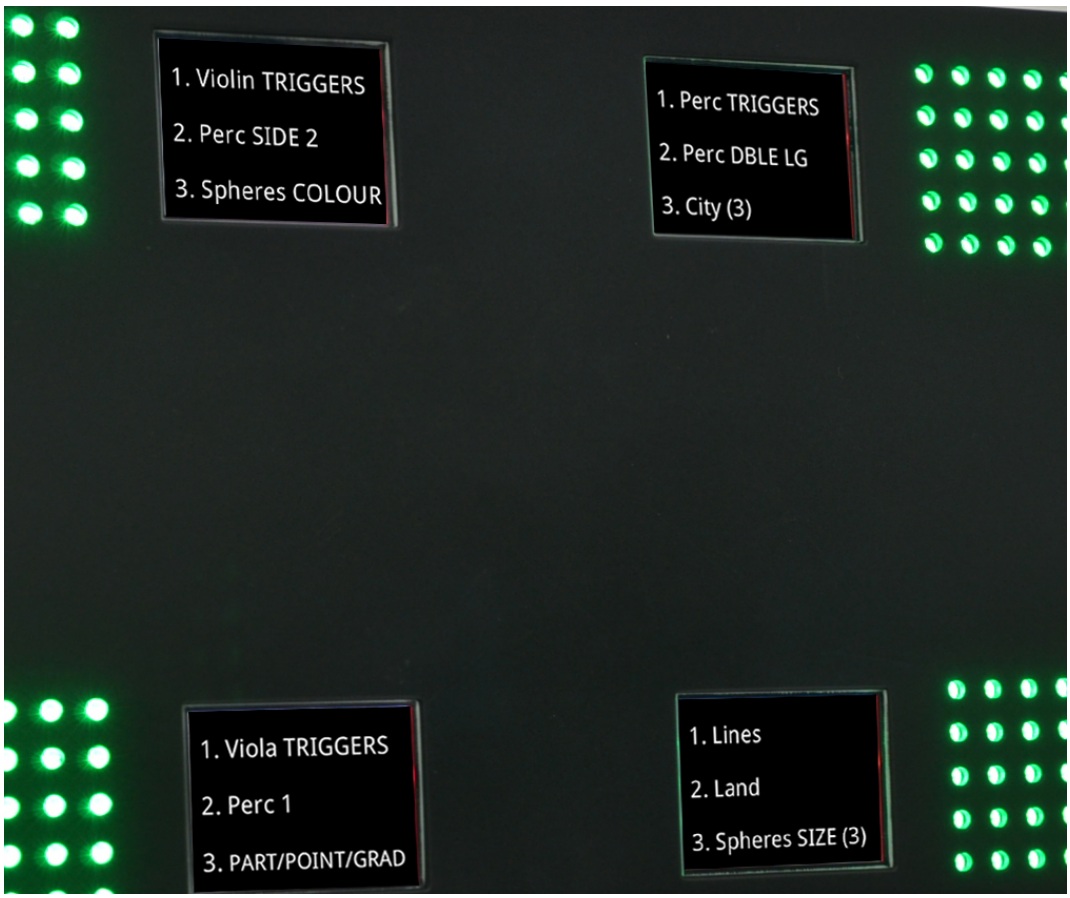

Figure 46. TFT images to display unit 1's mappings in *A Stark Mind*. Labels 1, 2 and 3 represent the mappings for each of the piece's three sections.

For examples, the four macro controls (see Figure 46) allow for visual score patterns to be started and stopped. The motor imagery selector extends the choices in a number of ways, for example:

- Assigning a score pattern to either the string instruments or the percussion

- Reversing the movement of a score patterns across the screen from left to right to right to left, or vice versa. Also reversing movement across the screen horizontally (a reversal in movement is mapped to a different playing technique for the musicians)

Motor imagery detection is based on approximating alpha band-power in the run up to initial positive SSVEP detection. The BCMI performer focuses either on relaxation or imagining squeezing their right hand whilst they make an SSVEP selection. Once positive SSVEP is detected at time *t=0* alpha band-power related to motor imagery is collected for the window of *t – 3sec* until *t + 1secs* providing a window of 4 seconds for comparison against the classifier trained during the calibration stage. The additional one-second delay for detecting motor imagery is factored into synchronisation patterns for macro controls and acts as a delayed extension to controls over visual effects. For *A Stark Mind* delayed control is acceptable as score patterns fade-in and out to create smooth visual transitions. Likewise amplitude control is also smoothed to result in more visually rounded results that are in keeping with the flow of the piece.

Performance is synchronised with a global clock that determines the control options and associated effects at certain times during performance. A selection of screenshots from the graphical score of *A Stark Mind* are shown in Figure's 47 & 48 and provide an insight into how some of the mapping controls are translated into the graphical score. The first of these, Figure 47, is taken from section 1 of the piece. Here, there are three elements of the score that link directly to each instrument. The moving red lines are for the viola to follow as the move across the display, the blue patterns are for the violin and the green for the percussion. For example the violin plays a 4-note broken arpeggio (representing the broken sides of the blue cube) that shifts in pitch as the cube traverses across the screen vertically. Each element is triggered by one of the icons from the first SSVEP stimuli unit

(see Figure 46). The manner in which they are presented is determined by motor imagery extension, for example the directional movement of the patterns across the screen. And the visual effects are controlled via the icons from the second SSVEP stimuli unit and global effect parameters are controlled via affective response.

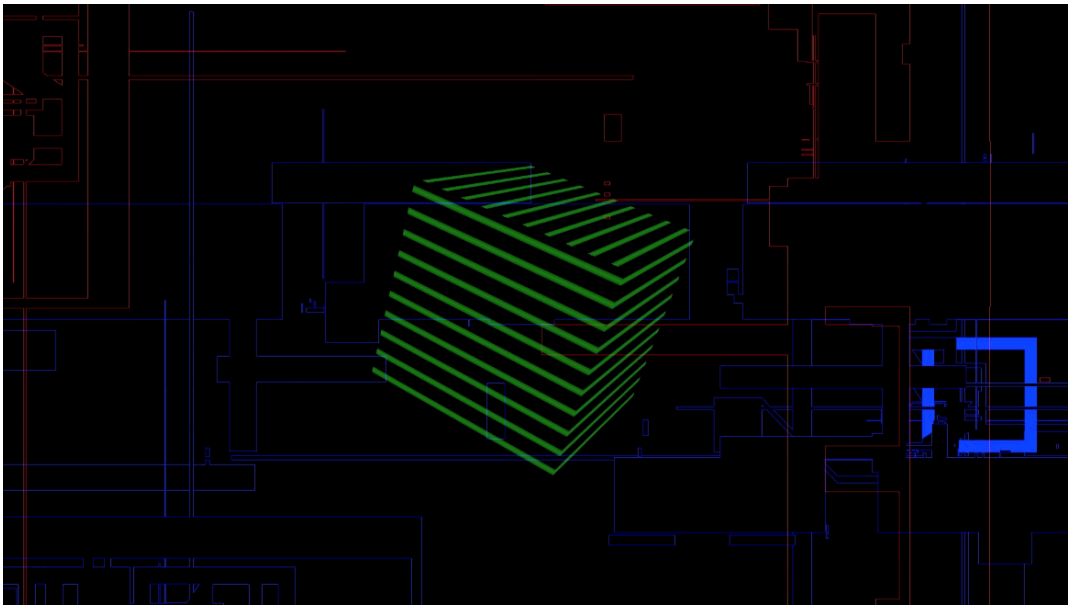

Figure 47. Screenshot of the graphic score from section 1 of *A Stark Mind.*

Figure 48 represents a screenshot taken from the second section of the piece. In this section both string instruments follow the outer lines of the turquoise coloured pattern that moves from left to right across the screen. During this section the macro controls (via SSVEP stimuli unit 1) trigger patterns for the percussive score (see Figure 46), although motor imagery can re-assign them to the string players by swapping the corresponding colours. Effects that determine the attributes of the outer lines and the shading (which in turn shape the resulting music) are controlled by icons from the second SSVEP stimuli unit, and again affective response is mapped to global parameters.

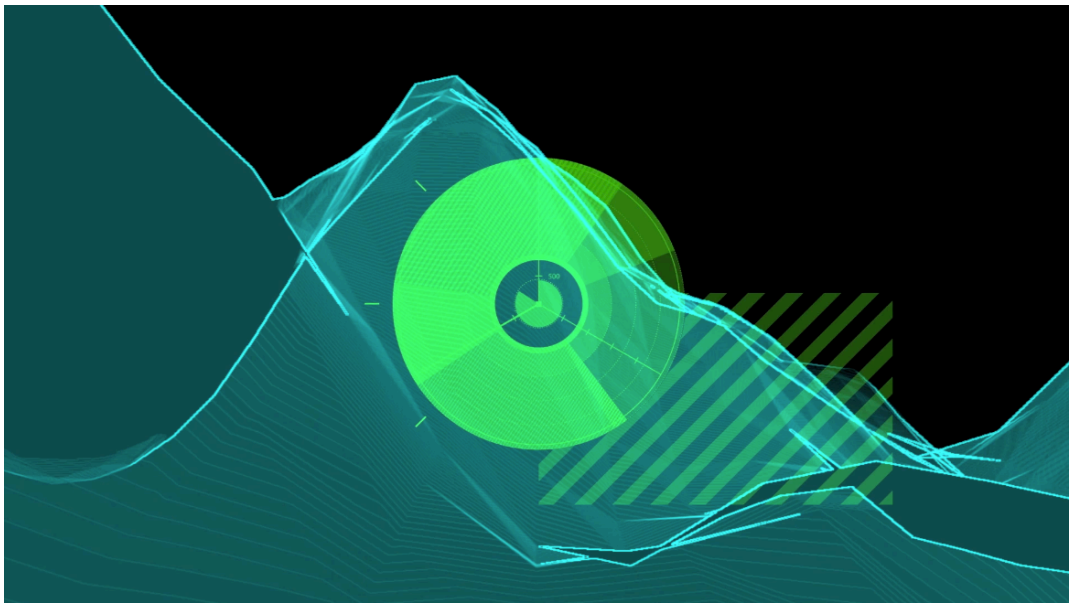

Figure 48. Screenshot of the graphic score from section 2 of *A Stark Mind.*

7.3.3.2 Passive Control Mappings

Affective response is monitored throughout the performance and AV measures are averaged across windows of approximately 10 seconds as indicators of mood. Changes in mood from one window to the next are mapped to two primary parameters, playback speed and contrast. Continuous changes in tempo, known to induce changes in arousal, can be off-putting for listeners are also difficult for musicians to adapt to in real-time. To reflect changes in arousal, the movement of score patterns speeds up or down, across a scaled range, and depends on relative inverse-arousal changes across windows in order to create smooth transitions. For example, when a lower measure of arousal is recorded the score patterns speed up and the resulting tempo increases in an attempt to escalate user arousal and reinforce mental activation. Arousal is also reflected in the ranges of the visual effect parameters that are controlled by SSVEP and MI. Positive arousal changes are mapped to trigger smaller effect ranges and negative arousal changes are mapped to select wider ranges. Examples of parameter ranges include brightness exposure of a score pattern or the level of visual distortion.

Changes in valence are mapped to the visual contrast, again in an inverted manner. Positive valence is mapped to low image contrast and vice versa. For both arousal and valence rules within transformation algorithms are applied to move baseline corrections at key stages in the performance to reduce repetitive settings. Both arousal and valence mappings, although indicative of AV in terms of descriptors, are again selected for their artistic potential within the piece and instead of inducing affect-matching responses within the system they attempt to induce a steady state of arousal and valence, one that lies roughly in the middle of the 2-dimensional affective space (Figure 33), within the constraints of the mapping ranges.

7.3.4 Discussion and observations

BCMI user feedback from early iterations of *A Stark Mind* indicated that the addition of the motor imagery and SSVEP techniques was initially challenging to successfully control as the motor imagery mappings commands across the SSVEP channels varied widely, and more time was required to make decisions before executing control. It was proposed that motor imagery mappings be closely tied to the SSVEP commands as a whole to create simpler choices, such as the two-states 'more' or 'less', to make the playability of the interface feel more intuitive.

Performing the BCMI in *A Stark Mind* requires intensive concentration across a range of modes including the control methods, the visual projections and the subsequent music. To provide some respite the transformation algorithms were modified so that the performer does not need to be actively engaged at all times, as score patterns are looped during playback, and this allows the user to rest for periods of contemplation in between periods of control, as required. This allows the performer to determine the level of engagement that is in turn reflected in the levels of intensity and the dynamics of the score and music. This freedom of control (deciding when to rest, when to act etc.) whilst always still being

in control is an important element of the user experience, as the user is not bound by time-based stimuli control.

During performance it was observed that the SSVEP control provided greater accuracy than motor imagery, although experimental evidence is required to corroborate this. As a result future BCMIs should not rely on motor imagery control for macro musical commands until accuracy is appropriately addressed, such as those involving musical structure and arrangement, where failure is more likely to frustrate a user. It was also observed that, again, the use of affective response provides a suitable platform for secondary control parameter changes, as it provides an unpredictable element of controlled surprise that in turn can affect decision-making in active control.

Embedding EEG feedback into the visual interface was not required for *A Stark Mind* as it was felt important that the user should feel less dependent on the technology to help them feel connected to the expressive elements of the performance, i.e. the visual projections and the music. Instead, feedback for the BCMI performer is offered through these two mediums, the projections and the music. Control changes during *A Stark Mind* do not need to be particularly fast at the music of the piece is designed to be drone-like, sweeping between different musical states. However, accuracy was still of high importance. A more leisurely approach to the speed of control was chosen to allow the BCMI more time to connect with the audiovisual modes external to the BCMI input again this suited the slow transitions of the graphic score. This approach was intended to lessen the concentration required to perform the piece, a requirement in many of the previous BCMIs in this thesis (e.g. *Flex* and *Activating Memory*), and allow the BCMI user to spend time reflecting on control due to the importance of immersing themselves in the audiovisual experience as a neuro-feedback exercise to inform control decisions and affective states as the piece progresses. In one respect this allows the BCMI to take a more passive role in the performance of the piece, especially from an audience's perspective, although perhaps not

as much as the role of the BCMI in *The Space Between Us.* Another advantage of this approach, coupled with the other elements of the performance is that although the BCMI acts at the conductor and arranger of the piece, its use is one of a number of elements on stage that contribute to the overall performance. An audience's attention is not entirely focused towards the BCMI performer (as it is in *Flex* for example), and the BCMI performer can be viewed as an equal part of the ensemble. This helps present the BCMI performer in the same light as one of the musicians, even if the method of control is not fully comprehended by an audience, their perspective encompasses four people focused on their instruments in front of them, whether acoustic or digital (see Figure 49).

Figure 49. Photo of A Stark Mind performance. Three musicians and a BCMI performer (second from right) preparing for a performance of A Stark Mind at the 11th International Symposium on Computer Music Multidisciplinary Research (CMMR), Plymouth, UK, 16th June 2015.

7.4 Conclusions

JoyBeat validates the hypothesis that SSVEP and affective responses are suitable for combination in an active/passive hybrid BCMI. No added cognitive effort is necessary and an interesting method of mapping mood indicators to music is achieved. The implications for creating a mood-induced neuro-feedback loop within an otherwise active BCMI presents an interesting area of both scientific and artistic exploration beyond *joyBeat* where AV mappings are merely indicative of changes in affective state.

Joybeat also demonstrates how a BCMI can be integrated with standardised music making tools, such as a drum machine and a step-sequencer. Although control is less tactile than hardware drum machines the BCMI showcases how traditional electronic music making tools can be successfully adapted for brainwave control. This could be expanded in future work to include other forms of music platforms, such as synthesisers, score creation interfaces, mixing desks, DJ applications.

Expanding the control in *joyBeat* to encompass a third dimension is made possible with the hybrid BCMI developed for the performance piece *A Stark Mind*. This is the first (to the author's knowledge) reported hybrid BCMI where two simultaneous active methods of control are combined to extended control alongside one passive control method.

A Stark Mind can also be considered as the culmination of BCMI development towards addressing performing with BCMI systems. Like *Activating Memory* and *The Space Between Us* music control is extended to acoustic instrumentation. However, in contrast with these two earlier works *A Stark Mind* adds two new elements to BCMI performance. Firstly, control is extended to live visual projections, which in turn control the musical outcomes. This not only adds an interesting visual dimension to the performance but it also helps communicate brainwave control to an audience in an artistic and non-technical way.

Secondly, the BCMI is framed on-stage as one of the performing instruments, contributing to the combined performance of the musical ensemble. Where the BCMI performers in *Activating Memory* are almost taking control over the string quartet, and the BCMI system in *The Space Between Us* is presented as a anonymous interface that conducts its work in hiding, the BCMI performer in *A Stark Mind* sits on-stage as the leader of the ensemble. This helps take the audience's main focus away from the motionless BCMI performer throughout performances and helps provide an impression of the BCMI performer as much a master of their musical craft as either the string players or percussionist, as they all face towards the score responding in their own unique way.

With regards to combining methods of control in a hybrid BCMI it remains to be seen as to what extent both the accuracy and control time of active control are affected, but *A Stark Mind* demonstrates that, although the motor imagery extension may not be as accurate as SSVEP control, it is a useful tool for extending control and thus adding more creative features to BCMI mappings. As mentioned the effect on control accuracy and response time through the addition of motor imagery provide a useful avenue for further work. However, there appears to be no direct affect on active control through the addition of affective measurement, and any impediment is likely to arise only from any cognitive distraction from the resulting musical mappings.

7.5 Summary

This chapter presents research towards developing hybrid BCMI systems that successfully apply more than one dimension of brainwave control over music, positively addressing **RQ5.** Previous studies of hybrid BCI control are evaluated taking into account the implications of combing control methods for music when a hybrid approach is applied to BCMI systems.

joyBeat, a hybrid BCMI for control over a drum machine and setup sequencer demonstrates how SSVEP control can be combined with affective responses to expand the musical outcomes of a BCMI. Software has been developed that interfaces brainwave signals to control a musical engine featuring a drum synthesiser and sequencer, a new form of mapping that goes towards addressing **RQ1**. Control signals are quantised in time with live playback creating a musical instrument that can be manipulated on the fly.

A Stark Mind is a performance piece that adds to the control on offer with *joyBeat* with a third dimension of control, motor imagery via ERD. Here motor imagery extends SSVEP control instead of reinforcing it (as in previous hybrid BCIs), creating more input channels and thus providing a creative approach towards addressing **RQ2**. The simultaneous methods of active control are successfully utilised for controlling a live graphical score to conduct an ensemble of musicians, also adding a new visual element that helps communicate brainwave control to an audience in an interesting and artistic way, directly addressing **RQ3**. Software has been developed that maps three dimensions of brainwave control to a visual engine for synchronised control to a dynamic visual score suitable for live performance.

Further investigation into the effects of combined brainwave control methods on accuracy and usability is recommended.

This work in this chapter concludes the body of research in this thesis. The future implications and impact on the field are discussed in chapter 8, which summarises the conclusions of the research.

Chapter 8: Conclusions

This final chapter summarises the body of research and the conclusions reached throughout the thesis. Contributions to knowledge are listed, including those that lie outside of the research questions raised in chapter 1. Finally, several recommendations are made to help inform the continuation of similar research in the future.

8.1 Research outcomes

This thesis set out to explore how brainwave control can be creatively applied in music making activities, particularly with regards to live performance, in both solo and collaborative settings. A series of BCMIs has been developed, each one addressing a particular area of this enquiry and attempting to improve and/or expand control in both practical and creative ways, and improve the presentation of BCMI technologies to public audiences.

At the beginning of this study a review of previous BCMI research was conducted to help outline an initial framework for investigation. SSVEP, a method of eliciting active control, was selected due to its suitability for providing explicit user control, a factor that could be objectively measured towards improving the first BCMI iteration, *Flex* presented in chapter 4. The *Flex* BCMI demonstrated that a portable, low-cost BCMI could be realised, albeit with the drawback of poor signal accuracy. The mappings of *Flex* attempt to capitalise on this poor accuracy, but the piece exemplifies how even limited control can be extended for arranging a live electronic music performance and diffuse music across a multi-channel loudspeaker system, an application not previously reported in literature.

The combination of stimuli rendering difficulties and signal quality from the low-cost EEG device used for *Flex* informed the design of a new SSVEP stimulus unit. The unit functions independently to a host PC and can generate a more precise, brighter flicker than the computer screens commonly used in BCMI and this subsequently generates a stronger SSVEP response. An upgrade to the pro-sumer grade EEG device was explored in order to improve on the level of control required for music making with SSVEP. An experiment was conducted to validate the accuracy and response time available with the SSVEP stimulus unit across three EEG hardware platforms. The results indicate that even with a minimal electrode setup and a simple calibration process a high level of accuracy is achievable.

The results of the experiment informed the development of the *Activating Memory* BCMI, a multi-user system for four BCMI users and a string quartet. A direct one-to-one mapping strategy was employed which utilises the accuracy and response time corroborated in the SSVEP experiment and when combined across four users created an interesting collaborative method of using brainwave control over direct acoustic instrumentation.

Activating Memory showcases the strengths of the SSVEP BCMI, which is robust, reliable and can be used by multiple users for simultaneous control over music. However, control was still limited as only one input channel can be affected at a time. With a view to integrating other brainwave control methods with the SSVEP technique a study into the effects of affective responses to music was undertaken, and this results in a number of exciting findings. Firstly it was shown that affective states measured via EEG can be successfully used to select music with specific emotional connotations, which when selected in real-time might be used to help regulate a user's affective state; a novel form of neurofeedback. Further to this a BCMI was developed that adapted to the affective responses of two users in a live performance setting, a performer and a member of the audience. Data from a live performance of *The Space Between Us* indicates that such a system can be used to monitor affective changes within participants during music making. This might be used to generate emotionally charged shared experiences, especially when individual musical preferences are taken into account.

The study of affective responses to music showed that this passive method of brainwave control could provide a useful addition to SSVEP control, especially as it requires no additional stimuli or cognitive effort. The *joyBeat* hybrid BCMI demonstrates how the two methods can be used for simultaneous active/passive control over a software based drum machine and step-sequencer, a novel emulation of a staple tool in electronic music. In addition to SSVEP and affective response the research concludes with a second hybrid BCMI that expands control across three dimensions with the addition of motor imagery

through ERD, a mental task-based method of controlling alpha activity in the brain's motor cortex. This was implemented for the performance piece *A Stark* Mind where motor imagery was used to extend SSVEP control options, and this differs from traditional hybrid BCI systems where a secondary active control method is commonly used to reinforce the primary method. As such, *A Stark Mind* is the culmination of expanding BCI control in this thesis by using a hybrid approach, and also presents a novel approach to controlling music in real-time through control over a dynamic visual score, which is projected on-stage for both an ensemble of musicians to follow and an audience to see.

Initially, a number of research questions were proposed and a summary of how the body of research has addressed them is provided here:

RQ1. How can brainwave measurement provide a suitable platform for control over musical parameters?

Suitable brainwave stimulation and analysis techniques have been selected towards providing a variety of control functions that have been applied to music. Active brainwave control, through the SSVEP technique, formed the initial area of investigation due to its suitability for real-time applications and its superior control accuracy over other active control methods, as reported in the review of the literature (chapter 2). This primary form of control was optimised through the development of a new SSVEP stimulus unit that paved the way for investigating other methods of brainwave control that could contribute to music making in other creative ways, notably motor imagery. Aside from active control a method of passive control, affective response, was found to provide a meaningful platform for interfacing with music generation. The 6 BCMIs outlined throughout the thesis all contribute to addressing this question.

RQ2. How can mapping strategies be designed for BCMIs with limited inputs?

The mapping strategies used in the BCMIs throughout the thesis contribute to stabilising brainwave information to be used for musical control. In the BCMIs presented musical control is never simply restricted to control over an individual musical parameter that is isolated from a wider musical context, instead there is control of musical features within performance and composition systems that contain a wide number of musical features that are mapped to brainwave control. For example, the *Flex* BCMI employs a variety of mapping techniques that allow for different types of musical control. These include direct amplitude control, minimum threshold triggering and the use of mapping rules, such as the randomisation feature. A more direct mapping feature is applied for *Activating Memory*, and the piece showcases how synchronised mappings can be useful for direct control over live instrumentation, across multiple BCMI users.

The two BCMIs in chapter 6 are controlled with extrapolating meaning across 2-dimensions relating to affective states. The range of inputs is divided into 12 distinct states, and this provides a foundation for mapping music associated to the different emotional descriptors of each state. The BCMIs in chapter 7 go somewhat beyond the scope of this research question. Within these systems control is no longer limited as methods of control are merged to create hybrid systems. In fact, there is an abundance of control on offer and for *A Stark Mind* the mappings need to be restrained to allow the user with the capacity to successfully control the piece. This exemplifies how the eventual direction of the research went beyond the scope of the initial aims.

RQ3. Can BCMIs be improved for use away from laboratory settings and in more traditional music performance environments?

The *Flex* BCMI (chapter 4) was developed towards providing a portable system that could be used for musical performances. *Flex* was successfully performed live a number of times however some issues for improvement were raised. The inclusion of a higher quality EEG

measuring platform and the development of the new SSVEP stimulus unit (see chapter 5) helped provide a stable BCMI system that could perform reliably outside of controlled environments and in unpredictable setting. An experiment measuring SSVEP response across three EEG measuring platforms and a number of subjects showed high levels of accuracy and reasonable response time were achievable, two of the key system criteria out lined in section 2.13. The findings of the experiment conducted to validate the performance of the new stimuli unit for SSVEP control were implemented into the *Activating Memory* BCMI, which takes into account the accuracy and response time available, as confirmed by the experiment. The new units were also successfully integrated in both hybrid BCMI systems for *joyBeat* and *A Stark Mind*. Following on from Flex the remaining BCMI were all designed with portability in mind, allowing for easy transportation of BCMI systems for performances to take place across Europe (further details in section 8.2.2).

The BCMI testing in chapter 5 using EEG, in unpredictable environments and a minimal number of electrodes contributed towards designing systems with ease of setup/use in mind, another key system criterion.

The BCMI applications presented in the thesis also address the issue of usability, in terms of the *feel* of the interface, another system criterion. Visual feedback is adopted for SSVEP control, and an intuitive method of combining both motor imagery and SSVEP that expands control is designed. Applying measures of affect in BCMIs provides an interesting interpretation of a user's mood as a control mechanism, with emotional congruency creating a unique experience in terms of musical control, communication and interaction.

The issue of performing with brainwaves is explored in all of the BCMI systems used for live performances in the thesis. As initially acknowledged the common procedures of BCI control are neither visually engaging nor do they inherently communicate the nature of

control, especially in a concert setting. *Flex* makes a point of amplifying the visual elements that are available, i.e. facial expressions, whereas Activating *Memory* addresses this issue with the addition of musicians and the stage layout to help communicate the interaction with an audience. *The Space Between Us* is designed to allow for expressive performance elements to be factored into live performance as EEG is measured only during specific windows, and *A Stark Mind* uses a method of visually projecting control through the use of a dynamic graphic score.

RQ4. Is a multi-brain BCMI feasible for collaborative music making?

This question has been explicitly addressed through the two BCMI systems *Activating Memory* and *The Space Between Us,* both of which demonstrate novel ways of communication and interaction using BCMI. In the former system 4 BCMI users exert simultaneous control over individual musicians, and the musical performance is synchronised so that SSVEP selection, control and the resulting music becomes a collaborative and shared process. The success of recording brainwave information simultaneously across a group of users provided the technical confidence to use this approach when exploring affective control in chapter 6. *The Space Between Us* monitors EEG signals from two participants simultaneously. Instead of controlling individual musical elements (as in *Activating Memory*) the measures contribute to a singular musical outcome, one that is shared between the users. These two different systems contribute to a new application of BCMI control, multi-brain BCMI, again another system criteria which has been met, which has so far been largely unreported.

RQ5. Can brainwave detection methods be combined to expand control in BCMI systems?

The investigation of passive control in chapter 6 is done towards finding a suitable secondary method of control for use alongside SSVEP. The area of affective responses was

chosen for its suitability in a musical context and because it can be easily incorporated into a SSVEP BCMI from a usability perspective, as no extra user effort is required. With regards to providing a user with a feeling of more control passive control does not offer this to the same extent as active control, but nonetheless offers an interesting area for creative exploitation, as shown in the *joyBeat* BCMI. *A Stark Mind* employs a third control method, motor imagery through ERD, and this provides increased control options and without any additional external stimuli. The accuracy of this method is not as high as SSVEP control and the mappings are designed to offer extended controls where a lower accuracy will not be too harmful to the performance of the piece. Here, control is widened through the expansion of more input channels but more importantly, through the combination of different control paradigms the three dimensions of control are layered on top of each other. This allows for simultaneous control over multiple input channels, a form of brainwave-polyphony perhaps, that truly expands the control in BCMI.

8.2 Contributions

This section outlines the novel contributions of this thesis, followed by a general summary of contributions arising from the research.

8.2.1 Novel contributions

- Design of a low-cost, portable SSVEP BCMI system for quadraphonic concert performance (chapter 4)
- An experiment verifying SSVEP accuracy and response time across 3 EEG hardware platforms (chapter 5)
- A new external SSVEP stimulus unit for BCMI applications (chapter 5)
- A four user SSVEP multi-brain BCMI that controls score selection performed by a string quartet for live concert performance
- A pilot study corroborating the method of detecting affective states (outlined in section 3.2.2) for use in a real-time BCMI for selection of music with crowd sourced emotional meta-tags (from the *Stereomood* project)
- Implementation of a two user multi-brain BCMI system for live concert performance that approximates affective states of a performer and audience member and selects music in response. *The Space Between Us* (chapter 6)
- Implementation of a hybrid BCMI combining SSVEP and affective state detection for music control. *joyBeat* (chapter 7)
- A method of combining simultaneous SSVEP and motor imagery control for expanded music control (chapter 7) in a hybrid BCMI alongside affective state detection. *A Stark Mind* (chapter 7)

8.2.2 General contributions

- **Approaches to (and implications of) mapping brainwaves to music**

A series of new approaches to BCMI have been presented throughout the thesis. Ultimately, the aims of the BCMIs were to explore new control mechanisms however in certain instances the outcomes of the systems go some way beyond this. For example, *Activating Memory* not only demonstrates an application of a multi-brain BCMI, it also provides a unique platform for musical interaction for patients with severe disabilities who are otherwise excluded from such activities, as demonstrated with the *ParaMusic Ensemble*. Likewise, the affective BCMIs outlined in chapter 7 not only demonstrate how affective measures can be used as input to BCMIs, but also how emotions during musical listening and performance can play a part in creating unique and both individualised and shared musical experiences. The issue of presenting BCMI technologies to audiences and communicating brainwave control have been addressed to a relatively successful degree. Feedback from performances of Flex (4.4.3) informed how *Activating Memory* was staged and provided the spark behind the idea for incorporating more visual methods of communication, a concept also realised through the graphical score in *A Stark Mind.*

- **BCMI development**

6 unique BCMI systems have been developed as part of the body of research. All of the individual elements of the systems have been configured to work in in conjunction with each other, across a wide range of platforms towards meeting the objectives of each piece.

- **Software development**

Chapter 4:

  - EEG processing. A Brainbay model for real-time 4-channel SSVEP detection that scales SSVEP signals between a^{min} and a^{max} to MIDI values. Used in the *Flex* BCMI

- GUI. A Pure Data Gem application that hosts SSVEP stimuli and real-time EEG feedback for user control. See section 3.2.1
- Transformation algorithm. Pure Data program that applies a number of mapping strategies to controlling the music of *Flex*. This includes some generative functionality and randomised mapping assignment. See section 4.4.2
- Musical engine. Pure Data programs embedded into a custom made Integra Live project. The engine hosts over 60 recorded samples with bespoke tools for sound manipulation and multi-channel diffusion. See section 4.4.1

Chapter 5:

- EEG processing. A Matlab Simulink model for conducting the SSVEP experiment (outlined in section 5.1) across 3 EEG platforms (see section 2.3). The model synchronises the recording of data with the onset of icon flickering
- SSVEP stimulus unit programming. A program was developed for the units to run the experimental paradigm outlined in section 5.1
- Communication tools. A Pure Data patch communicated synchronisation data between Matlab Simulink and the SSVEP stimulus unit. Section 5.1
- *Activating Memory* BCMI. Software for integrating four BCMI systems into Activating Memory, outlined in detail in section 5.3.7, including score selection and transformation algorithm to select icon with the longest recorded positive response

Chapter 6:

- EEG processing. A Matlab Simulink model for detecting and classifying affective responses in EEG. See section 3.2.2.1.
- Transformation algorithm. A Pure Data patch was developed for mapping affective states to music playback for the *Affective Jukebox* and score selection for *The Space Between Us*
- Performance software. A segmented application was built in Pure Data for the performance of *The Space Between Us*. The application was separated across three laptop PCs to allow data capture synchronisation, score playback sync and for performing live audio DSP across the microphone inputs for the piano

Chapter 7:

- EEG processing. A Matlab Simulink model for simultaneous detection of 8 SSVEP channels and affective states (as per 2.6.1 and 2.6.2) for *joyBeat*. See section 7.2. A second model was developed with additional motor imagery from ERD classification for *A Stark Mind* (as per 2.6.3). See section 7.3
- Transformation algorithm. A Pure Data program for mapping simultaneous SSVEP control and affective responses to a drum machine and step-sequencer. See section 7.3.3
- Music engine. An FM synthesiser and step sequencer was developed and programmed into a drum machine to receive real-time EEG control data. See section 7.3.3
- GUI. A Pure Data GEM interface for the *joyBeat BCMI* user presenting the step-sequencer and EEG feedback

- Transformation Algorithm. A Pure Data program for mapping SSVEP, affective response and motor imagery from ERD to control over a visual engine for *A Stark Mind*. See section 7.3.2
- Visual engine. A Resolume project for dynamic generative visual design, video manipulation and graphical effects controlled by Pure Data program. See section 7.3.3

- **Hardware development**

A new SSVEP stimulus unit has been proposed and developed; contributing towards the experiment conducted in section 5.1 and the BCMI systems in sections 5.3, 7.2 and 7.3.

A technical report of the unit is presented in section 5.2

- **Experimentation**

An experiment comparing SSVEP responses across three EEG platforms (see section 2.3 for details) is presented in section 5.1.

Data recorded during a live performance of *The Space Between Us* is analysed in section 6.4.4.

- **Music composition**

Three new musical compositions, designed explicitly for BCMI control, have been produced as part of the research, *Flex, The Space Between Us* and *A Stark Mind.* Audiovisual representations of these are presented in Appendix 1.

- **Performances**

A number of performances have occurred throughout the project in relation to the development and presentation of the BCMIs presented in this thesis. These performances

also contribute towards promoting public engagement with the fields of BCMI and music technology. A selection of performances is summarised here:

Flex. FACT venue, Liverpool UK. 3/6/2014

Activating Memory. Music Tech Fest. St. Luke's London. 6/9/2014

The Space Between Us. 9th Conference on Interdisciplinary Musicology, Staatliches Institut for Musikforschung, Berlin, Germany, 5/12/14

A Stark Mind. The 11th International Symposium on Computer Music Multidisciplinary Research (CMMR) Music, Mind, and Embodiment. 16/6/2015

A number of individuals were given opportunities to perform with the BCMIs presented in this thesis. They include:

The Bergersen String Quartet – numerous recitals of *Activating Memory,* 2014 - 2015

String quartet featuring members of the Ten Tors Orchestra - *Activating Memory,* 15/6/15

The Paramusic Ensemble – *Activating Memory,* 18/7/15

Numerous members of the Brain ensemble (names anonymised) – numerous recitals of *Activating Memory,* 2014 - 2015

Weiwei Jin – Piano for *The Space Between Us,* 5/12/14

Fiona Miller - Vocalist for *The Space Between Us,* 5/12/14

Pierre Largeron - Violin for *A Stark Mind Us,* 16/6/15

Esther Coorevits - Viola for *A Stark Mind Us,* 16/6/15

Weiwei Jin - Percussion for *A Stark Mind Us,* 16/6/15

- **Research collaborations**

Areas of the research allowed for collaborative projects to be undertaken that are unlikely to have occurred otherwise. In particular these can be summarised as:

The Paramusical Ensemble – A project with staff and patients at the Royal Hospital for Neuro-Disability, London, UK.

The *Affective Jukebox* – A pilot study conducted in collaboration with Dr. Duncan Williams from Plymouth University.

Activating Memory – A BCMI system developed in collaboration with the composer Eduardo Miranda.

The Space Between Us – A multi-user BCMI for live performance. Music composed in collaboration with Weiwei Jin of De Montfort University.

- **Impact**

One of the most important outcomes from the research was the implementation of a multi-user BCMI for patients with varying degrees of paralysis. A project was undertaken with staff and patients at the Royal Hospital for Neuro-Disability, London, UK. After a number of individual and group sessions to familiarise users with the technology and to calibrate the system, four patients formed the *ParaMusical Ensemble*, making up the multi-brain BCMI quartet for a performance of *Activating Memory* (with the Bergersen String Quartet), taking place on 18/7/15. This performance was hosted by the hospital as an internal event for staff and other patients.

Elements of the research project were featured on television and radio programmes broadcasted both nationally and internationally. These included:

SSVEP Controlled BCMI: Featured on BBC Click, BBC News website, BBC Radio 4, BBC World Service, The Daily Telegraph newspaper, The Metro newspaper, The Daily Mail newspaper, various online news websites.

Affective Jukebox: An iteration of this project was featured on UK TV's The Gadget Show (Channel 5). First aired on 2/3/15.

8.3 Recommendations for Future Work

The suggestions for future work made throughout the thesis are summarised here:

- Future experiments testing user response against the SSVEP stimulus unit could investigate SSVEP stimuli at higher frequencies for potentially increased user comfort along with a high duty-cycle, which other studies have indicated can also increase amplitude response.
- A comparative study of EEG measuring devices is useful to the field. The selection of platforms for the SSVEP experiment was limited by access to systems. Future experiments could easily adopt the same conditions for testing other hardware devices and platforms against the stimuli units.
- SSVEP amplitude control is a particularly useful feature for BCMI. Investigating a^{max} as well as a^{min} values (alongside user ability to control amplitude within this range) across users presents a useful area for investigation. The study of real-time feedback is likely to be of importance here.
- It seems likely that both that response time and accuracy can be improved with more electrodes placed over the visual cortex region. The experiment in section 5.1 tested SSVEP response in one electrode channel replicating a quick and straightforward equipment setup procedure. However, the dry electrodes in platform 1 require no gel or solution and can be inserted into a brain cap prior to use. Therefore a few additional electrodes are unlikely to significantly contribute to the overall setup time and preparation of the user. An experiment would be useful to test this hypothesis given the platform's ease of use and already faster response times, two factors both useful for practical BCMI.
- From the results of the experiment in section 5.1 a calibration stage where a wider rage of frequencies is tested against before optimal frequencies are automatically

selected for the session presents itself as a useful development. This could be realised through an automated extension to the current Pure Data calibration program, in synchrony with an updated Arduino sketch for controlling the SSVEP stimulus unit.

- Collaborative outcomes of music making using BCMIs have been introduced in the thesis. For example, *Activating Memory* provides a platform for the musical interaction between four BCMI users, and *The Space Between Us* offers a method of directing music in response to the affective measures of multiple users. Both of these systems provide the foundation for future investigations into behavioural and emotional patterns between towards designing both generic individualised and BCMI interaction paradigms.
- Following on from the development of *A Stark Mind,* future investigations into this method of hybrid BCMI would benefit from corroborating the accuracy of the motor imagery method used. Further to this the affects of combining multiple dimensions of control on individual methods during hybrid control is so far largely unreported. Investigations into this area would benefit also the field.
- Finally, the foundations have been laid for exploring a variety of brainwave control methods for BCMI. Following on from this project it is expected that the field of BCMI will continue to evolve as strong artistic visions lead the way for brainwave control to be applied in new and exciting music making applications.

References

Aftanas, L. I. and S. A. Golocheikine (2001). "High-resolution EEG investigation of meditation." Neuroscience Letters 310(1): 4.

Aftanas, L. I., N. V. Reva, L. N. Savotina and V. P. Makhnev (2006). "Neurophysiological Correlates of Induced Discrete Emotions in Humans: An Individually Oriented Analysis." Neuroscience and Behavioral Physiology 36(2): 119-130.

Ahn, M., M. Lee, J. Choi and S. C. Jun (2014). "A Review of Brain-Computer Interface Games and an Opinion Survey from Researchers, Developers and Users." Sensors (Basel) 14(8): 14601-14633.

Allison, B. Z., C. Brunner, C. Altstatter, I. C. Wagner, S. Grissmann and C. Neuper (2012). "A Hybrid ERD/SSVEP BCI for Continuous Simultaneous two Dimensional Cursor Control." Journal of Neuroscience Methods 209(2): 299-307.

AlZoubi, O., R. A. Calvo and R. H. Stevens (2009). “Classification of EEG for Affect Recognition: An Adaptive Approach”. 22nd Australasian Joint Conf. Artificial Intelligence.

Amiri, S., R. Fazel-Rezai and V. Asadpour (2013). "A Review of Hybrid Brain-Computer Interface Systems." Fazel-Rezai, R. Advances in Human-Computer Interaction 2013: 1-8.

Amiri, S., Rabbi, A., Azinfar, L. and R. Fazel-Rezai (2013). "A Review of P300, SSVEP, and Hybrid P300/SSVEP Brain- Computer Interface Systems." Brain-Computer Interface Systems – Recent Progress and Future Prospects. InTech.

Arakawa, K., S. Tobimatsu, H. Tomoda, J. Kira and M. Kato (1999). "The Effect of Spatial Frequency on Chromatic and Achromatic Steady-State Visual Evoked Potentials." Clinical Neurophysiology 110(11): 1959-1964.

Ayaz, H., P. A. Shewokis, S. Bunce and B. Onaral (2011). “An Optical Brain Computer Interface for Environmental Control”. Engineering in Medicine and Biology Society, EMBC, 2011 Annual International Conference of the IEEE.

Babadi, B., S. M. McKinney, V. Tarokh and J. M. Ellenbogen (2012). "DiBa: A Data-Driven Bayesian Algorithm for Sleep Spindle Detection." Biomedical Engineering 59(2): 483-493

Baier, G., T. Hermann and U. Stephani (2007). "Event-Based Sonification of EEG Rhythms in Real Time." Clinical Neurophysiology 118(6): 1377-1386.

Baier, G., T. Hermann and U. Stephani (2007). “Multi-Channel Sonification of Human EEG”. 13th International Conference on Auditory Display. Montréal, Canada.

Barrett, M. (2006). "'Creative collaboration’: an ‘eminence’ study of teaching and learning in music composition " Psychology of Music 34(2): 195 - 118.

Besson, M. and F. Fai'ta (1995). "An Event-Related Potential (ERP) Study of Musical Expectancy: Comparison of Musicians With Nonmusicians." Journal Of Experimental Psychology 21(6): 1278-1296.

Besson, M. and F. Macar (1987). "An Event-Related Potential Analysis of Incongruity in Music and Other Non-Linguistic Contexts." Psychophysiology 24(1): 14-25.

Besson, M. and D. Schön (2003). “Comparison Between Language and Music. The Cognitive Neuroscience of Music”. I. a. Z. Peretz, R.J. New York, Oxford University Press.

Beverina, F., G. Palmas, S. Stefano, F. Piccione and S. Giove (2003). "User Adaptive BCIs: SSVEP and P300 based Interfaces." PsychNology Journal 1(4): 331-354.

Boulanger, R. (2000). “The CSound Book”. Cambridge, MA, The MIT Press.

Bradley, M. and P. Lang (2007). “The International Affective Digitized Sounds (2nd Edition; IADS-2): Affective ratings of sounds and instruction manual”. Technical report B-3. Gainesville, Fl., University of Florida, .

Cahn, B. R. and J. Polich (2006). "Meditation States and Traits: EEG, ERP, and Neuroimaging Studies." Psychological Bulletin 132(2): 180-211.

Calhoun, G. L. and G. R. McMillan (1996). “EEG-based Control for Human-Computer Interaction”. 3rd Annual Symposium on Human Interaction with Complex Systems, Dayton, Ohio, USA.

Cambria, E., A. Hussain and C. Eckl (2011). “Taking refuge in your personal sentic corner”. Proceedings of the Workshop on Sentiment Analysis where AI meets Psychology (SAAIP). Chiang Mai, Thailand.

Camurri, A., G. Volpe, G. D. Poli and M. Leman (2005). "Communicating Expressiveness and Affect in Multimodal Interactive Systems." IEEE Multimedia 12(1): 43-53.

Cecotti, H., I. Volosyak and A. Gräser (2010). “Reliable Visual Stimulation on LCD Screens for SSVEP based BCI”. The 2010 European Signal Processing Conference (EUSIPCO-2010). Aalborg, Denmark.

Chanel, G., J. Kronegg, D. Grandjean and T. Pun (2006). “Emotion Assessment: Arousal Evaluation Using EEG’s and Peripheral Physiological Signals”. Université de Genève. 4105: 530-537.

Cherry, E. C. (1953). "Some Experiments on the Recognition of Speech with one and with two Ears." Journal of the Acoustical Society of America 25: 975-979.

Chowning, J. M. (1973). "The Synthesis of Complex Audio Spectra by means of Frequency Modulation." Journal of the Audio Engineering Society 21(7): 526-534.

Ciardi, F. C. (2004). "sMax: A Multimodal Toolkit for Stock Market Data Sonification." Proceedings of the 10th International Conference on Auditory Display (ICAD2004). Sydney, Australia.

Combaz, A., C. Chatelle, A. Robben, G. Vanhoof, A. Goeleven, V. Thijs, M. M. Van Hulle and S. Laureys (2013). "A Comparison of Two Spelling Brain-Computer Interfaces Based on Visual P3 and SSVEP in Locked-In Syndrome." PLoS ONE 8(9): e73691.

Cook, A., M. (2002). Future directions in assistive technology. “Assistive Technology: Matching Device and Consumer for Successful Rehabilitation”. M. J. Scherer. Washington, DC, US, American Psychological Association. xiii: 269-279.

Crowley, K., A. Sliney, I. Pitt and D. Murphy (2010). “Evaluating a Brain-Computer Interface to Categorise Human Emotional Response”. 10th International Conference on Advanced Learning Technologies (ICALT), 2010 IEEE.

Daly, I., A. Malik, F. Hwang, E. Roesch, J. Weaver, A. Kirke, D. Williams, E. Miranda and S. J. Nasuto (2014). "Neural correlates of emotional responses to music: an EEG study." Neuroscience Letters 573: 52-57.

Daly, I., D. Williams, F. Hwang, A. Kirke, A. Malik, E. Roesch, J. Weaver, E. Miranda and S. J. Nasuto (2014). "Investigating music tempo as a feedback mechanism for closed-loop BCI control." Brain-Computer Interfaces 1(3-4): 158-169.

Davis, S., P. Allen, M. Mann and T. Cox (2011). "Musical Moods: A Mass Participation Experiment for Affective Classification of Music". 12th International Society for Music Information Retrieval Conference (ISMIR 2011): 741–746.

de Campo, A., R. Höldrich, A. Wallisch and G. Eckel (2007). "New Sonification Tools for EEG Data Screening and Monitoring". 13th International Conference on Auditory Display, Montreal, Canada.

Dean, T. L. and M. P. Wellman (1991). "Planning and Control". M. Kaufmann Publishers.

Desain, P. and H. Honing (1989). "The Quantization of Musical Time: A Connectionist Approach." Computer Music Journal: 56-66.

Dillman Carpentier, F. R. and R. F. Potter (2007). "Effects of Music on Physiological Arousal: Explorations into Tempo and Genre." Media Psychology 10(3): 339-363.

Donchin, E., W. Ritter and W. C. McCallum (1978). "Cognitive Psychophysiology: The Endogenous Components of the ERP". Event- Related Brain Potentials in Man. E. Callaway, P. Tueting and S. H. Koslow, Academic Press.

Duncan, A. (2001). "EEG Pattern Classification for the Brain-Computer Music Interface". PhD thesis, Glasgow University.

Duvinage, M., T. Castermans, M. Petieau, T. Hellinger, G. Cheron and T. Dutoit (2013). "Performance of the Emotiv Epoc Headset for P300-based Applications." BioMedical Engineering OnLine 12(56).

Eaton, J. and E. Miranda (2012). "New Approaches in Brain-Computer Music Interfacing: Mapping EEG for Real-Time Musical Control". Music, Mind, and Invention Workshop, The College of New Jersey, USA.

Eaton, J. and E. Miranda (2014). "Expanding on Brain Control: A Real-Time Hybrid BCMI for Drum Machine Combining active (SSVEP) and Passive (Affective Response) Brainwave Control". 9th Conference on Interdisciplinary Musicology – CIM14, Berlin, Germany.

Eaton, M. (1971). "Bio-Music: Biological Feedback, Experiential Music System". Kansas City, USA, Orcus.

Ferrari, M. and V. Quaresima (2012). "A Brief Review on the History of Human Functional Near-Infrared Spectroscopy (fNIRS) Development and Fields of Application." NeuroImage 63(2): 921-935.

Fisher, R. S., G. Harding, G. Erba, G. L. Barkley and A. Wilkins (2005). "Photic- and Pattern-Induced Seizures: A Review for the Epilepsy Foundation of America Working Group." Epilepsia 46(9): 15.

Fitch, W. T. and G Kramer (1994). "Sonifying the Body Electric: Superiority of an Auditory Display over a Visual Display in a Complex, Multivariate System". Auditory Display – Sonification, Audification, and Auditory Interfaces. G. Kramer. Reading, UK, Addison-Wesley: 307.

Franco, F., J. S. Swaine, S. Israni, K. A. Zaborowska, F. Kaloko, I. Kesavarajan and J. A. Majek (2014). "Affect-Matching Music Improves Cognitive Performance in Adults and Young Children for Both Positive and Negative Emotions." Psychology of Music 42(6): 869-887.

Friberg, A., R. Breson and J. Sundberg (2006). "Overview of the KTH Rule System for Musical Performance." Advances in Cognitive Psychology 2(2-3): 145 - 161.

Friman, O., I. Volosyak and A. Gräser (2007). "Multiple Channel Detection of Steady-State Visual Evoked Potentials for Brain-Computer Interfaces." IEEE Transactions on Biomedical Engineering 54(4).

Garnett, G. and C. Goudeseune (1999). "Performance Factors in Control of High-Dimensional Spaces". International Computer Music Conference (ICMC 1999), Beijing, China.

George, L. and A. Le´cuyer (2010). "An Overview of Research on "Passive" Brain-Computer Interfaces for Implicit Human-Computer Interaction". International Conference on Applied Bionics and Biomechanics ICABB 2010 Venice Italy.

Giraldo, S. and R. Ramirez (2013). "Brain-Activity-Driven Real-Time Music Emotive Control". 3rd International Conference on Music & Emotion (ICME3), Jyväskylä, Finland, Luck, G & Brabant, O.

Goudeseune, C. (2002). "Interpolated Mappings for Musical Instruments." Organised Sound 7(02).

Grierson, M. (2008). "Composing With Brainwaves: Minimal Trial P300 Recognition as an Indication of Subjective Preference for the Control of a Musical Instrument". International Computer Music Conference (ICMC), Belfast, Ireland.

Guger, C., G. Edlinger and G. Krausz (2011). "Hardware/Software Components and Applications of BCIs". Recent Advances in Brain-Computer Interface Systems. R. Fazel-Rezai. Rjeka, Croatia: 1-24.

Hammer, E. M., S. Halder, B. Blankertz, C. Sannelli, T. Dickhaus, S. Kleih, K.-R. Müller and A. Kübler (2012). "Psychological Predictors of SMR-BCI Performance." Biological Psychology 89(1): 80-86.

Henver, K. (1936). "Experimental Studies of the Elements of Expression in Music." American Journal of Psychology 48(2): 22.

Herrmann, C. S. (2001). "Human EEG Responses to 1–100 Hz Flicker: Resonance Phenomena in Visual Cortex and their Potential Correlation to Cognitive Phenomena." Experimental Brain Research 137(3-4): 346-353.

Herwig, U., P. Satrapi and C. Schönfeldt-Lecuona (2003). "Using the International 10-20 EEG System for Positioning of Transcranial Magnetic Stimulation." Brain topography 16(2): 95-99.

Hinterberger, T. and G. Baier (2004). "POSER: Parametric Orchestral Sonification of EEG in Real-Time for the Self-Regulation of Brain States". International Workshop on Interactive Sonification, Bielefeld.

Hu, X. and J. S. Downie (2010). "Improving Mood Classification in Music Digital Libraries by Combining Lyrics and Audio". Proceedings of the 10th Annual Joint Conference on Digital Libraries. Gold Coast, Queensland, Australia, ACM: 159-168.

Hunt, A. and R. Kirk (2000). "Mapping Strategies for Musical Performance". Ircam Centre Pompidou.

Hunt, A. and M. M. Wanderley (2003). "Mapping Performer Parameters to Synthesis Engines." Organised Sound 7(02).

Hunt, A., M. M. Wanderley and R. Kirke (2000). “Towards a Model for Instrumental Mapping in Expert Musical Interaction”. International Computer Music Conference (ICMC), San Francisco, USA.

Huster, R. J., S. Debener, T. Eichele and C. S. Herrmann (2012). "Methods for Simultaneous EEG-fMRI: An Introductory Review." Journal of Neuroscience 32(18): 6053-6060.

Jeong, J. (2002). "Nonlinear Dynamics of EEG in Alzheimer's Disease." Drug Development Research 56(2): 57-66.

Kamiya, J. (1962). “Conditioned Discrimination of the EEG Alpha Rhythm in Humans”. Western Psychological Association. San Franscisco, USA.

Kamiya, J. (1968). "Conscious Control of Brain Waves." Psychology Today 1: 56–60.

Kirke, A. and E. Miranda (2011). “Combining EEG Frontal Asymmetry Studies with Affective Algorithmic Composition and Expressive Performance Models”. International Computer Music Conference (ICMC 2011), Huddersfield, UK.

Kluge, T. and M. Hartmann (2007). “Phase Coherent Detection of Steady-State Evoked Potentials: Experimental Results and Application to Brain-Computer Interfaces”. Neural Engineering, 3rd International IEEE/EMBS Conference on Neural Engineering

Knapp, R. B. and P. R. Cook (2005). “The Integral Musical Controller: Introducting a Direct Emotional Interface to Gestural Control of Sound Synthesis”. International Computer Music Conference (ICMC). Barcelona, Spain.

Knapp, R. B. and H. Lusted (1990). "A Bioelectric Controller for Computer Music Applications." Computer Music Journal 14(1): 42-47.

Knobloch, S. and D. Zillmann (2002). "Mood Management via the Digital Jukebox." Journal of Communication 52(2): 351-366.

Kübler, A. and J. R. Müller (2007). “An Introduction to Brain–Computer Interfacing”. Toward Brain–Computer Interfacing. G. Dornhege, J. del Millán, T. Hinterberger, D. J. McFarland and K. R. Müller, MIT Press: 1 - 25.

Lamont, A. and T. Eerola (2011). "Music and Emotion: Themes and Development." Musicae Scientiae 15(2): 139-145.

Lee, P.-L., C.-H. Yeh, J. Y.-S. Cheng, C.-Y. Yang and G.-Y. Lan (2011). "An SSVEP-Based BCI Using High Duty-Cycle Visual Flicker." IEEE Transactions on biomedical engineering 58(12): 10.

Leslie, G. and T. Mullen (2011). “MoodMixer: EEG-based Collaborative Sonification”. International Conference on New Interfaces for Musical Expression (NIME), Oslo, Norway.

Lin, Y. P., C. H. Wang, T. P. Jung, T. L. Wu, S. H. Jeng and J. R. Duann (2010). "EEG-Based Emotion Recognition in Music Listening." IEEE Transactions on Biomedical Engineering 57(7): 9.

Lipscomb, S. D. (1999). "Cross-Modal Integration: Synchronization of Auditory and Visual Components in Simple and Complex Media." The Journal of the Acoustical Society of America 105(2).

Liu, Y., X. Jiang, T. Cao, F. Wan, P. Un Mak, P. Mak and M. I. Vai (2012). “Implementation of SSVEP Based BCI with Emotiv EPOC”. Virtual Environments Human-Computer Interfaces and Measurement Systems (VECIMS), IEEE.

Loy, G. (1985). "Musicians Make a Standard: The MIDI Phenomenon." Computer Music Journal: 8-26.

Lucier, A. (1976). “Statement on: Music for Solo Performer (1971)”. Biofeedback and the Arts: Results of Early Experiments. D. Rosemboom. Vancouver, Aesthetic Research Center of Canada.

Magee, W. L. (2006). "Electronic Technologies in Clinical Music Therapy: A Survey of Practice and Attitudes " Technology and Disability 18(3): 7.

McFarland, D. J., L. A. Miner, T. M. Vaughan and J. R. Wolpaw (2000). "Mu and Beta Rhythm Topographies During Motor Imagery and Actual Movements." Brain topography 12(3): 177-186.

McFarland, D. J., W. A. Sarnacki and J. R. Wolpaw (2010). "Electroencephalographic (EEG) Control of Three-Dimensional Movement." Journal of Neural Engineering 7(3): 036007.

Mehta, N. A., S. H. S. Hameed and M. M. Jackson (2010). "Optimal Control Strategies for an SSVEP-Based Brain-Computer Interface." International Journal of Human-Computer Interaction 27(1): 85-101.

Miranda, E. and A. Brouse (2005). "Interfacing the Brain Directly with Musical Systems: On Developing Systems for Making Music with Brain Signals." Leonardo 38(4): 331-336.

Miranda, E. and A. Brouse (2005). “Toward Direct Brain-Computer Musical Interfaces”. International Conference on New Interfaces for Musical Expression (NIME), Vancouver, BC, Canada.

Miranda, E., K. Sharman, K. Kilborn and A. Duncan (2003). "On Harnessing the Electroencephalogram for the Musical Braincap." Computer Music Journal 27(2): 80 - 102.

Miranda, E. and V. Soucaret (2008). “Mix-It-Yourself with a Brain-Computer Music Interface”. 7th ICDVRAT with ArtAbilitation, Maia/Porto, Portugal.

Miranda, E. and M. Stokes (2004). "On Generating EEG for Controlling Musical Systems." Biomedizinische Technik 49(1): 75-76.

Miranda, E. R. (2001). “Composing Music with Computers”. Oxford, UK, Focal Press.

Miranda, E. R., W. L. Magee, J. J. Wilson, J. Eaton and R. Palaniappan (2011). "Brain-Computer Music Interfacing (BCMI): From Basic Research to the Real World of Special Needs." Music and Medicine 3(3): 134-140.

Miranda, E. R. and M. M. Wanderley (2006). “New Digital Musical Instruments: Control And Interaction Beyond the Keyboard”. A-R Editions.

Misra, U. K. and J. Kailta (2005). “Clinical Electroencephalography”. India, Elsevier.

Misulis K, E. (1997). “Essentials of Clinical Neurophysiology”. Boston, MA, USA, Butterworth-Heinemann.

Mozart, W. A. (1793). “K. Anh 294d”. Berlin, Amsterdam, Johann Julius Hummel.

Müller, K.-R., M. Krauledat, G. Dornhege, G. Curio and B. Blankertz (2004). "Machine Learning Techniques for Brain-Computer Interfaces." Biomed. Tech 49(1): 11-22.

Müller, K.-R., M. Tangermann, G. Dornhege, M. Krauledat, G. Curio and B. Blankertz (2008). "Machine Learning for Real-Time Single-Trial EEG-Analysis: From Brain–Computer Interfacing to Mental State Monitoring." Journal of Neuroscience Methods 167(1): 82-90.

Näätänen, R. (1990). "The Role of Attention in Auditory Information Processing as Revealed by Event-Related Potentials and other Brain Measures of Cognitive Function." Behavioral and Brain Sciences 13(2): 201-288.

Neuper, C., R. Scherer, M. Reiner and G. Pfurtscheller (2005). "Imagery of Motor Actions: Differential Effects of Kinesthetic and Visual–Motor Mode of Imagery in Single-Trial EEG." Cognitive Brain Research 25(3): 668-677.

Ng, K. B., A. P. Bradley and R. Cunnington (2012). "Stimulus Specificity of a Steady-State Visual-Evoked Potential-Based Brain–Computer Interface." Journal of Neural Engineering 9(3): 036008.

Nidal, K. and A. Malik, S. eds. (2015). "EEG/ERP Analysis: Methods and Applications". Boca Raton, U.S.A, CRC Press, Taylor and Francis Group.

Niedermeyer, E. and F. H. e. Lopes da Silva (1987). "Electroencephalography". Urban and Schwartzenber, Munich, Germany.

Ojanen, M., J. Suominen, T. Kallio and K. Lassfolk (2007). "Design Principles and User Interfaces of Erkki Kurenniemi's Electronic Musical Instruments of the 1960's and 1970's". New Interfaces for Musical Expression (NIME07), New York, USA.

Ouzounian, G., B. Knapp and E. Lyon (2011). "Music for Sleeping and Waking Minds". Concert Notes. Dublin, Ireland, Science Gallery Dublin and The League of Consciousness Providers.

Ox, J. (2010). "A 21st-Century Pedagogical Plan for Artists: How Should We Be Training Artists for Today?". Leonardo 43(1): 2.

Panicker, R. C., S. Puthusserypady and Y. Sun (2011). "An Asynchronous P300 BCI With SSVEP-Based Control State Detection." EEE Transactions on Biomedical Engineering 58(6): 8.

Pfurtscheller, G., B. Z. Allison, C. Brunner, G. Bauernfeind, T. Solis-Escalante, R. Scherer, T. O. Zander, G. Mueller-Putz, C. Neuper and N. Birbaumer (2010). "The Hybrid BCI." Frontiers in Neuroscience 4: 30.

Pfurtscheller, G., C. Brunner, A. Schlögl and F. L. Da Silva (2006). "Mu Rhythm (de) Synchronization and EEG Single-Trial Classification of Different Motor Imagery Tasks." Neuroimage 31(1): 153-159.

Pfurtscheller, G., T. Solis-Escalante, R. Ortner, P. Linortner and G. R. Muller-Putz (2010). "Self-Paced Operation of an SSVEP-Based Orthosis With and Without an Imagery-Based Brain Switch: A Feasibility Study Towards a Hybrid BCI." Neural Systems and Rehabilitation Engineering, IEEE Transactions on 18(4): 409-414.

Pratt, R. R., H. H. Abel and J. Skidmore (1995). "The Effects of Neurofeedback Training with Background Music on EEG Patterns of ADD and ADHD Chidren." International Journal of Arts Medicine 4(1): 24 - 31.

Ramirez, R. and Z. Vamvakousis (2012). "Detecting Emotion from EEG Signals Using the Emotive Epoc Device". Brain Informatics Lecture Notes in Computer Science, Springer: 175-184.

Regan, D. (1989). "Human Brain Electrophysiology: Evoked Potentials and Evoked Magnetic Fields " Science And Medicine. New York; London: Elsevier.

Rentfrow, P. J. and S. D. Gosling (2003). "The Do Re Mi's of Everyday life: The Structure and Personality Correlates of Music Preferences." Journal of Personality and Social Psychology 84(6): 1236-1256.

Rolls, E. T. (2012). "Neuroculture: On the Implications of Brain Science". Oxford University Press, UK.

Rolvsjord, R. (2004). "Therapy as Empowerment." Nordic Journal of Music Therapy 13(2): 99-111.

Rosenboom, D. (1972). "Method for Producing Sounds or Light Flashes with Alpha Brain Waves for Artistic Purposes." Leonardo 5(2): 4.

Rosenboom, D. (1990). "Extended musical interface with the human nervous system." Revised electronic monograph. Original, Leonardo monograph series. 1997. San Francisco (1).

Russell, J. A. (1980). "A Circumplex Model of Affect." Journal of Personality and Social Psychology 39(6).

Russell, J. A. and L. F. Barrett (1999). "Core affect, prototypical emotional episodes, and other things called emotion: Dissecting the elephant." Journal of Personality and Social Psychology 76(5).

Salimpoor, V. N., M. Benovoy, G. Longo, J. R. Cooperstock and R. J. Zatorre (2009). "The Rewarding Aspects of Music Listening are Related to Degree of Emotional Arousal." PLoS One 4(10): e7487.

Sammler, D., M. Grigutsch, T. Fritz and S. Koelsch (2007). "Music and Emotion: Electrophysiological Correlates of the Processing of Pleasant and Unpleasant Music." Psychophysiology 44(2): 293-304.

Sawyer, R. K. (2006). "Group Creativity: Musical Performance and Collaboration." Psychology of Music 34(2): 148 - 165.

Scherer, K. R. (2004). "Which Emotions Can be Induced by Music? What Are the Underlying Mechanisms? And How Can We Measure Them?" Journal of New Music Research 33(3): 239-251.

Schmidt, L. A. and L. J. Trainor (2001). "Frontal Brain Electrical Activity (EEG) Distinguishes Valence and Intensity of Musical Emotions." Cognition and Emotion 15(4): 13.

Schuett, J. H., R. J. Winton and B. N. Walker (2014). "Comprehension of Sonified Weather Data Across Multiple Auditory Streams". The 20th International Conference on Auditory Display (ICAD-2014). New York, USA.

Sebastiani, L., A. Simoni, A. Gemignani, B. Ghelarducci and E. L. Santarcangelo (2003). "Autonomic and EEG Correlates of Emotional Imagery in Subjects with Different Hypnotic Susceptibility." Brain Research Bulletin 60(1–2): 151-160.

Sitaram, R., H. Zhang, C. Guan, M. Thulasidas, Y. Hoshi, A. Ishikawa, K. Shimizu and N. Birbaumer (2007). "Temporal Classification of Multichannel Near-Infrared Spectroscopy Signals of Motor Imagery for Developing a Brain–Computer Interface." NeuroImage 34(4): 1416-1427.

Society, A. E. (1994). "American Electroencephalographic Society. Guideline Thirteen: Guidelines for Standard Electrode Position Nomenclature." Journal of Clinical Neurophysiology 11: 2.

Strehl, U., U. Leins, G. Goth, C. Klinger, T. Hinterberger and N. Birbaumer (2006). "Self-Regulation of Slow Cortical Potentials: A new Treatment for Children with Attention-Deficit/Hyperactivity Disorder." Pediatrics 118(5): e1530-1540.

Takahashi, T. and Y. Tsukahara (1976). "Influence of Color on the Photoconvulsive Response." Electroencephalography and Clinical Neurophysiology 41(2): 13.

Teitelbaum, R. (1976). "In Tune: Some Early Experiments in Biofeedback Music (1966-74)". Biofeedback and the Arts: Results of Early Experiments. D. Rosemboom. Vancouver, Aesthetic Research Centre of Canada Publications.

Teitelbaum, R. (2006). "Improvisation, Computers and the Unconscious Mind." Contemporary Music Review 25(5-6): 497-508.

Tenke, C. E. and J. Kayser (2005). "Reference-Free Quantification of EEG Spectra: Combining Current Source Density (CSD) and Frequency Principal Components Analysis (fPCA)." Clinical Neurophysiol 116(12): 2826-2846.

Teplan, M. (2002). "Fundamentals of EEG measurement." Measurement Science Review 2(2): 11.

van der Zwaag, M. D., J. H. D. M. Westerink and E. L. van den Broek (2011). "Emotional and Psychophysiological Responses to Tempo, Mode, and Percussiveness." Musicae Scientiae 15(2): 250-269.

Van Essen, D. C., C. H. Anderson and D. J. Felleman (1992). "Information Processing in the Primate Visual System: An Integrated Systems Perspective." Science 255(5403): 5.

Vidaurre, C., C. Sannelli, K.-R. Müller and B. Blankertz (2011). "Machine-Learning-Based Coadaptive Calibration for Brain-Computer Interfaces." Neural computation 23(3): 791-816.

Vogt, K., A. de Campo and G. Eckel (2007). "An Introduction to Sonification and its Application to Theoretical Physics". 3rd Congress of the Alps Adria Acoustics Association, Graz, Austria.

Volosyak, I., H. Cecotti and G. s. A. (2009). "Optimal Visual Stimuli on LCD Screens for SSVEP Based Brain-Computer Interfaces". 4th International IEEE EMBS Conference on Neural Engineering, Antalya, Turkey.

Vuoskoski, J. K. and W. F. Thompson (2012). "Who Enjoys Listening to Sad Music and Why?" Music Perception: An Interdisciplinary Journal 29(3): 311-317.

Wang, Y., R. Wang, X. Gao, B. Hng and S. Gao (2006). "A Practical VEP-Based Brain–Computer Interface." IEEE Transactions on biomedical engineering 14(2): 6.

Wang, Y., Y. T. Wang and T. P. Jung (2010). "Visual stimulus design for high-rate SSVEP BCI." Electronics Letters 46(15): 1057.

Wiedemann, H. R. (1994). "Hans Berger." European Journal of Pediatrics 153(10): 705-705.

Williams, D., A. Kirke, E. R. Miranda, E. Roesch, I. Daly and S. Nasuto (2014). "Investigating affect in algorithmic composition systems." Psychology of Music.

Wilson, J. J. and R. Palaniappan (2009). “Augmenting a SSVEP BCI Through Single Cycle Analysis and Phase Weighting”. 4th International IEEE EMBS Conference on Neural Engineering, Antalya, Turkey, IEEE EMBS.

Wilson, J. J. and R. Palaniappan (2011). "Analogue Mouse Pointer Control via an Online Steady State Visual Evoked Potential (SSVEP) Brain-Computer Interface." Journal of Neural Engineering 8(2): 025026.

Wolpaw, J. R. and N. Birbaumer (2006). “Brain–Computer Interfaces for Communication and Control”. Textbook of Neural Repair and Rehabilitation: Volume 1, Neural Repair and Plasticity. M. Selzer, S. Clarke, L. Cohen, P. Duncan and F. Gage. UK, Cambridge University Press. 1: 602-614.

Wolpaw, J. R., D. J. McFarland, G. W. Neat and C. A. Forneris (1991). "An EEG-Based Brain-Computer Interface for Cursor Control." Electroencephalography and Clinical Neurophysiology 78(3): 252-259.

Wu, D., C. Li, Y. Yin, C. Zhou and D. Yao (2010). “Mapping rules from EEG to Music”. M. C. f. t. B. S. R. t. M. S. b. Music. Journal of Computational Intelligence and Neuroscience.

Wu, D., C. Li, Y. Yin, C. Zhou and D. Yao (2010). "Music Composition from the Brain Signal: Representing the Mental State by Music." Computational Intelligence and Neuroscience: 267671.

Wu, D., C. Y. Li and D. Z. Yao (2009). "Scale-Free Music of the Brain." PLoS One 4(6): e5915.

Wu, Z., Y. Lai, Y. Xia, D. Wu and D. Yao (2008). "Stimulator Selection in SSVEP-Based BCI." Medical Engineering & Physics 30(8): 1079-1088.

Zander, T. O., C. Kothe, S. Welke and M. Roetting (2009). “Utilizing Secondary Input from Passive Brain-Computer Interfaces for Enhancing Human-Machine Interaction”. Proceedings of the 5th International Conference on Foundations of Augmented Cognition. Neuroergonomics and Operational Neuroscience: Held as Part of HCI International 2009. San Diego, CA, Springer-Verlag: 759-771.

Zeki, S. (1993). “A Vision of the Brain”. Oxford, Blackwell.

Zhang, Y., P. Xu, T. Lui, R. Zhang and D. Yao (2012). "Multiple Frequencies Sequential Coding for SSVEP-Based Brain-Computer Interface." Plosone 7(3): 9.

Zhu, D., J. Bieger, G. Garcia Molina and R. M. Aarts (2010). "A Survey of Stimulation Methods used in SSVEP-based BCIs." Computational Intelligence and Neuroscience: 702357.

Appendix 1

The digital media files in this appendix require suitable playback software for interaction. The open-source platform VLC[19] is recommended for viewing/listening the files.

The attached digital storage device includes the following files presented in the following directory structure:

- Chapter_4
  - Flex_documentary.mp4
  - Flex_quadraphonic_mix.wav
  - Flex_stereo_mix.wav
- Chapter_5
  - Activating_Memory_documentary.mp4
- Chapter_6
  - The_Space_Between_Us_performance.mp4
- Chapter_7
  - A_Stark_Mind_performance.mkv
  - joyBeat_overview.mp4

[19] http://www.videolan.org/vlc/index.en_GB.html

Appendix 2

A: Information and agreement

My name is Joel Eaton. I am a final year PhD student working under the supervision of Prof Eduardo Miranda, and with Dr David Bessell as second supervisor. If you have any questions please contact joel.eaton@postgrad.plymouth.ac.uk.

This document contains important information regarding the *Steady-State Visual Evoked Potential* (SSVEP) experiment I will be conducting as part of my doctoral research. Please read it thoroughly beforehand and keep it in a safe place, as it contains important information and contact details that are still relevant to you after the experiment has taken place.

Responsibility and negligence

By agreeing to take part in the experiment you are held in agreement to the fact that Plymouth University nor the staff undertaking the experiment are accountable or responsible for any damages, losses, or medical outcomes as a result of the experiment.

Risks involved

Gazing at flashing icons is known to trigger epileptic fits within a small percentage of epilepsy sufferers. However, if you have not already been diagnosed with epilepsy the likelihood of a fit occurring is extremely low (less than 1% of the population suffer from epilepsy and less than 50% of them suffer from epileptic fits). By agreeing to participate in this study you are also acknowledging the risks involved, which may still be prevalent even if you do not have a history of epilepsy, or a previous diagnosis. Therefore the following information is of the upmost importance. You are advised to read it carefully.

IMPORTANT: If you begin to feel nauseous, fatigued, dizzy, tired or experience any strange sensations that you do not consider normal **DO NOT CLOSE YOUR EYES**. This could increase your risk of having a seizure. Instead, immediately cover one eye with the palm of your hand and turn away from the flashing light (This reduces the number of brain cells that are stimulated and reduces the risk of a seizure happening). If you able to, say out loud the word SAFE, and this will enable the engineer to switch off any flashing stimuli and become aware of your condition.

Overview of experiment procedure

The experiment you are about to undertake forms part of a doctoral research project in monitoring brain wave responses. This study is interested in monitoring brain wave responses when a subject gazes at a flashing light. This experiment requires you to gaze at a number of flashing lights whilst a brain cap monitors your brain's responses. An engineer will instruct you, at regular intervals, to focus your gaze towards a particular array of flashing lights, and then to gaze away from the lights to a non-flashing object. The only requirements asked of you are to gaze towards and away from the flashing lights. Your brainwave data will be recording during the experiment. The data recorded contains no information or indications relating to your cognitive abilities, your eyesight or any medical insights regarding you as an individual. The main aim of the research is to test the suitability of the equipment used and the procedure of the experiment.

Right to withdraw

At any point during or after the experiment you have a right to withdraw from the process. Withdrawing after the experiment has taken place will remove your data permanently from the record. However this will not be done to any retrospective publications. A one-month cooling-off period exists from the day that the experiment

takes place for one whole calendar month. This month exists for you to change your mind and withdraw consent to your data being published. During this month your data will remain unpublished. Please email joel.eaton@postgrad.plymouth.ac.uk to withdraw to your data.

B: Consent Form and questionnaire

This document contains important information regarding potential effects of the methods used in the Brain-Computer Interface (BCI) SSVEP experiment. Please read it carefully and fill in the information fields prior to undertaking any tests.

The experiment uses flashing lights that you are required to gaze at. These are known to trigger mild epileptic fits in sufferers of epilepsy. Therefore if you are a sufferer of epilepsy, are prone to epileptic fits or other forms of fits you will not be allowed to participate in the tests.

Subjects with a history of epilepsy are strongly advised to declare this in the following information fields.

NAME:

DATE:

Q. Have you ever suffered from an epileptic fit, at any time in your life?

Please circle your answer

YES / NO

Q. Have you ever been diagnosed with epilepsy?

Please circle your answer

YES / NO

Q. Have you ever suffered from a fit of any nature, even if the nature is unknown?

Please circle your answer

YES / NO

SIGNED

By signing you are declaring that the information given above is as true an account as to your knowledge.