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Music and the Brain: Composing with the Electroencephalogram

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Music and the Brain: Composing with the Electroencephalogram

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Declaration

At no time during the registration for the degree of Research Masters has the author been registered for any other University award without prior agreement of the Doctoral College Quality Sub-Committee.

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Abstract

The field of brain-computer music interfaces have been expanding ever since the first development in the 1960s. Although many brain-computer music interfaces have been developed for the purpose of composing music, these systems have not been accessible to musicians due to the use of complex programming and signal processing mathematics. In addition, these systems have often focused on the process of composing music by allowing for specific note selection, or the formation of structure. While these systems are beneficial for those who cannot compose music the traditional way, such as those with motor disabilities, they do not offer a new compositional tool to those with full muscular control. This thesis aims to develop an interactive compositional tool using a brain-computer music interface, utilising methods and techniques that will make it accessible to musicians. An investigation into harnessing brainwaves for musical control has been explored, determining that the alpha and beta waves will be most appropriate for this system. Furthermore, a survey of current BCMI systems have been provided, concluding that the musification approach is best suited to harness the user's alpha and beta waves. This approach allows for a set of musical rules to be implemented, as well as allowing for the creation of music that is representative of the user's biological state. The system developed for this thesis used the alpha and beta waves to control parameters of a pre-composed composition. The composition featured elements which

were aimed to elicit a change in the user's brainwave frequency, such as a rise in pitch, rhythmic changes, and key changes. The frequency bands are mapped to the parameters of note velocity, chord changes, and key changes.

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Glossary

BCI	Brain-Computer Interface
BCMI	Brain-Computer Music Interface
EEG	Electroencephalogram
ERP	Event-Related Potential
FT	Fourier transform
fMRI	Functional Magnetic Resonance Imaging
MEG	Magnetoencephalogram
MI	Motor Imagery
MIDI	Musical Instrument Digital Interface
SSVEP	Steady-State Visual Evoked Potential
VR	Virtual Reality

Introduction

Imagine a world where we could create a melody in our head and have a computer compose it as we think. Unfortunately, this idea is rather far-fetched and technology has a long way to go before this becomes a reality as opposed to merely an idea. However, technology such as the brain-computer music interface (BCMI) is the initial move towards such a technological development. The BCMI comes from a cross-disciplinary field that combines the methodologies from the fields of Neuroscience and Computer Music. This technology can allow for a user to communicate and control musical instrument sounds or musical parameters via their brain signals. This thesis forms a collection of research focusing on the development of a BCMI system, with the aim to develop methods of integrating this technology into the compositional process to create an interactive composition tool.

One of the first pioneers to use this technology for musical purposes was Alvin Lucier, whose 1965 composition of *Music for Solo Performer* (Lucier, 1976) became referred to as the 'brain wave piece' (Straebel and Thoben, 2014). In preparation for his performance, Lucier set up sixteen loudspeakers that were all placed to touch percussion instruments; this included gongs, snare drums, timpani and even a metal can in which the loudspeaker was placed inside (Lucier, 1976). Lucier used the electroencephalogram (EEG), a method of recording brain signals, to record his alpha waves. Three electrodes were placed on his scalp in certain locations to obtain his alpha waves, which were transmitted directly through the loudspeakers (Straebel and Thoben, 2014). As the alpha waves flowed through the loudspeakers, the instruments resonated and thus created the composition, *Music for Solo Performer* (Lucier, 1976). As Lucier was predominantly a musician, no complex EEG detection or analysis tools were used. This made it suitable for a musician to understand, as a musician would not have training in such technology (Novello, 2012).

While there was no particular musical structure to this composition, Lucier (1976) stated that he would make musical decisions through the placement of loudspeakers or the choice of instruments or use of objects. Lucier (1976) also stated that the role of his assistant was volume control, channeling, and mixing, which formed the musical decisions. A traditional notated score was not feasible for such a composition, as many of the performances of this piece relied purely on the composers spoken instructions. However, much later he provided performers with a score which included a list of all the equipment required, how to place them, and a set of instructions (Lucier, 1980). Regardless, Lucier's intentions were not aiming to create a piece of music, but simply taking the EEG signals, amplifying them, and playing them back through loudspeakers connected to percussion instruments. There was no translation of the EEG data into musical structures, which is what the research of this thesis is interested in. However, this composition was well-suited to the experimental avant-garde compositional movement of the 1960s.

Following on from Lucier's work, Richard Teitelbaum explored the use of biofeedback, a method of electronically monitoring bodily functions, in his 1967 and 1968 compositions: *Spacecraft* and *In Tune.* The former composition, *Spacecraft,* uses the EEG signals, the performers breathing sounds, and heartbeat to create an electronic music texture (Rosenboom, 1997). The amplified EEG signals were used as a control source for a Moog analogue synthesiser (Nijholt, 2019). Similarly to Lucier's composition, this piece did not follow a score, although as described by Teitelbaum (1974) the composition was formed of the performers own consciousness. The latter composition, *In Tune,* began with the breathing sounds of the performers being softly amplified, before the introduction of their heartbeat gradually faded in. When the performer closed their eyes the alpha wave increased and triggered a loud, startling burst of electronic sounds coming from the loudspeaker placed in the room (Teitelbaum, 1974). By opening and closing their eyes, the performer was able to start and stop the sounds that were being produced. During the performance of this piece, Teitelbaum took the role of the conductor, by controlling the mixing, panning and crossfading, to the merging of the brainwaves, heartbeats, and breaths (Teitelbaum, 1974). Much like Lucier’s work, Teitelbaum’s intentions was not to create a piece of music, but to use the amplified EEG signals as a control source for a Moog analogue synthesiser.

Inspired by the work of Teitelbaum and Lucier, David Rosenboom began to continue the exploration of the use of biofeedback in his composition, *Brainwave Music*, in 1974 (Nijholt, 2019). Rosenboom took the brainwave information and fed it to a sound synthesis system that generated sound, electronically, from scratch (Rosenboom and Paul, 1986; Nam et al., 2018). It has been stated that Rosenboom was the first composer with the intention to understand the brain signal for musical purposes (Novello, 2012). He analysed the possibilities and limitations of the EEG signal for the use of conscious control of generative music rules. This then lead to tools for conscious control over musical parameters. The majority of this time period can be characterised by the discovery of the control that the alpha wave offered and the modification of this control to musical compositions (Williams and Miranda, 2018).

A notable advancement towards a BCMI was the development of *BioMuse* (Knapp and Lusted, 1990), a hardware and software solution that allowed for real-time digital processing of bio-signals such as the EEG, muscle movement, and heartbeat (Eaton, 2016). This enabled one to convert these signals into MIDI (Musical Instrument Digital Interface) data (Miranda and Castet, 2014). MIDI is the standard protocol for sending music control data between devices such as synthesisers and computers (Eaton, 2016); this includes commands such as note-on, note-off, velocity and pitch (Eaton, 2016). Previous to this, mapping musical parameters and brainwaves would have been built into the hardware that was used, such as the Moog synthesiser (Miranda and Castet, 2014). The mappings were also pre-determined, meaning that they were fixed and extremely difficult to change or undo (Miranda and Castet, 2014). Fortunately, BioMuse provided a portable kit that not only digitally processes bio-signals, but it also converts these signals into MIDI data. This then created a MIDI controller based on bodily responses (Miranda and Castet, 2014). This development allowed for the EEG signal to be directly mapped to MIDI-enabled equipment, such as a sequencer or drum machine (Miranda and Castet, 2014). From the late 1980s, bursts of alpha activity were being sonified via a MIDI synthesiser, with the use of opening and closing the eyes to generate different amplitudes in alpha activity which was incorporated into compositions.

More recently, researchers have been utilising this technology for the purpose of composing music. Pinegger et al. (2017) developed a system that allowed the user to compose note-by note, similar to using music notation software such as MuseScore. The system used eye-gazing techniques where the user was able to select notes by simply gazing at the icon on a screen. While such system would not provide benefits to musicians who can compose music using music notation software, it could benefit people with physical disabilities who have limited or no muscle movement. In regard to this, there has been research focusing on the development of the BCMI to be used as a communication medium for those with physical disabilities, such as Miranda et al. (2011) system that allowed one to select a musical phrase on a screen using eye-gazing techniques. While this technology is certainly an advancement, these researchers are focusing on creating an interface for someone to interact with a computer without the need for a mouse or keyboard, as oppose to using this technology specifically to create musical compositions. Therefore, these systems do not provide any new aspects to the compositional process that cannot already be achieved without the use of this technology.

There has also been BCMI systems developed that allow for one to manipulate musical parameters using their brainwaves (Miranda and Soucaret, 2008; Eaton and Miranda, 2013). Miranda and Soucaret's (2008) BCMI allowed for a user to change the volume of two tracks using their alpha and beta waves. Despite there only being one parameter for the user to control, this system is a step forward in the development of a system for composers. Eaton and Miranda's (2013) BCMI system used eye-gazing technology to allow participants to select pre-composed phrases to form a game-like situation with another participant. While this system is suitable for the purpose it was developed for (multi-user BCMI system), the technology used is not appropriate for a composer whose skill set stems from music.

The aim of this thesis is to explore BCMI technology to create an interactive compositional tool that will be suitable for musicians to use. While the pioneers of the BCMI have developed tools using sonification, I wish to take the approach of musification as I will be mapping EEG signals to musical parameters as oppose to sound synthesisers.

This approach will enable composers to inject a new twist into their compositions through the use of their brainwaves, which would be unachievable without this technology. This will be achieved through the following research questions and aims.

Personal Motivations

The motivation behind this thesis lies within my curiosity and inquisitiveness of using this technology to aid my own practice. I am a classically trained musician who composes music with inspiration from the classical era to the romantic era. I am approaching this research from the perspective of a composer, determining the challenges and benefits of using this technology for compositional purposes. My main aim is to integrate this technology into the compositional process, whilst also maintaining the structure and musicality of western traditional music. Additionally, I am looking to explore the connection between the listener and the pre-composed music that will be playing. To do so, I want to extract features from the EEG data that are known to show some levels of relaxation and use this to trigger compositional devices that we might associate with that state. The integration of this technology will allow for a biological representation of the composers brain waves to be integrated into their composition; something which is unachievable through the traditional methods of composing music.

Research Aims

The main aims of this research are:

- To discuss and determine an appropriate method and technique that can be used to develop a BCMI system for an interactive compositional tool. A survey and discussion of relevant methods and techniques is provided in chapter one and chapter two.
- To develop a BCMI that can be used as an interactive compositional tool for pre-composed composition. This will be addressed in chapter three.

These aims are in support of the research questions which are as follows.

Research Questions

> **RQ1.** What are the creative and technical challenges and opportunities of harnessing EEG technology in a musical composition?

This research question will be addressed along with the first research aim in Chapters One and Two. More specifically, Chapter 1.1 will address the reason for using the EEG compared to other brain recording methods. Chapter Two particularly explores the approaches to harnessing brainwaves in music, with a survey discussing the challenges that may be encountered.

> **RQ2.** What compositional strategies and mapping techniques can be adopted to integrate brainwaves into the compositional process?

This question will be addressed throughout Chapter Two. In particular, this chapter will be discussing the compositional strategies and mapping techniques that current BCMI systems have used, and critically discussing them against criteria. This will determine what strategies and techniques will be best suited to a musician who would be using this system as an interactive compositional tool.

Methodology

This thesis will start with a detailed survey of existing research in the BCMI field and BCIs more generally. Insights from this survey will inform the design of the BCMI system in the later chapters. Chapter Two will explore composition within a BCMI, through a survey of current approaches that are used in current BCMI systems. This will allow for the exploration of the possibilities a BCMI can be used as an interactive compositional tool, through analysing the most common musical parameters and discovering how they can be integrated into a system. In addition, it will allow for research into appropriate methods that can be used to harness EEG technology. The software that will be used for the development of the system is the g.tec Sahara EEG electrode system, OpenVibe, and Max/MSP, which will all be introduced within the thesis.

Thesis Structure

The structure of this thesis begins with a background history of the BCMI to allow the reader to gain some required knowledge.

Chapter One explores the technical aspects of measuring brain signals and critically evaluates the methods that can be used. This chapter addresses both RQ1 and RQ2 as it delves into the technical challenges that could arise as well as exploring some interesting mapping techniques of current BCMI systems.

Chapter Two explores composition within a BCMI through a survey of approaches used to harness brainwaves in musical composition. This survey is critically discussed against criteria, placing the research into the perspective of the field. This chapter addresses both RQ1 and RQ2.

Chapter Three introduces the developed BCMI system for this thesis. This chapter details the development process, including the technical challenges and the compositional ideas and reasons behind these decisions. A discussion of the final system is then presented, bringing in the RQ's and emphasising how they were addressed.

Chapter Four is the conclusion for the entire thesis. It is formed of a summary of the thesis followed by an in-depth conclusion of the research aims and questions.

During this research project, the following papers have been published:

Horrell, R. (2020). "Music and the Brain: Composing Music with Electroencephalogram". *In Proceedings of the 7th International Conference on New Music Concepts* (ICNMC-2020). Treviso, Italy. (March 14-15, 2020).

Horrell, R. H. (2020). "An Interactive Compositional Tool using the Electroencephalogram". *Interactional Journal of Music Science, Technology and Art,* **2**(August, 2), 22-26.

Chapter One: Background Information

Overview:

This chapter provides the reader with an in-depth understanding of how the human brainwaves can be recorded, as well as discussing the most appropriate method of recording brainwaves for a BCMI. This method is then explained thoroughly and in relation to the development of a system for this thesis. An introduction to the brain-computer interface and brain-computer music interface is provided in this chapter.

1.1. Introduction to measuring brain signals

The first measurement of human brainwaves was in the 1920s when psychiatrist Hans Berger attached electrodes to his scalp and recorded the electrical fields generated by the neural activity of his brain (Miranda, 2006). Berger termed this method *electroencephalography* (EEG). Brainwaves are produced from the neural activity within the brain, which produces oscillations of rhythmic patterns (Sylwester, 2004). Neurons (the cells within the nervous system) communicate with one another to send and receive data to and from the brain. This communication between thousands of neurons produce oscillations of electrical signals, which can be recorded using methods such as the EEG (Sylwester, 2004). There are five widely recognised brainwaves which each oscillate at different frequency ranges (Figure 1.1). These frequencies will be explained in more depth in Chapter 1.2.

There are numerous methods used to measure brain activity, however, it is important to note that not all methods record the activity of neurons. It is also crucial to point out that some methods are invasive, meaning that electrodes have to be surgically installed and, therefore, is not explored in the thesis. Non-invasive methods involve electrodes being placed on the user's scalp, which is safe and harmless (Eaton, 2016).

Three non-invasive methods that are used to measure brain activity are the electroencephalogram (EEG), magnetoencephalogram (MEG) and the functional magnetic resonance imaging (fMRI). The EEG records the electrical signals of the brain which are produced by the neurons (Rowan and Tolunsky, 2003). The MEG records the magnetic fields that are generated by the neurons (Braeutigam, 2013), and the fMRI records brain activity by measuring the blood flow in the brain (van Erp et al., 2012). For use within a BCMI, it is important to take into consideration the research questions and aims and discuss each method in regard to these.

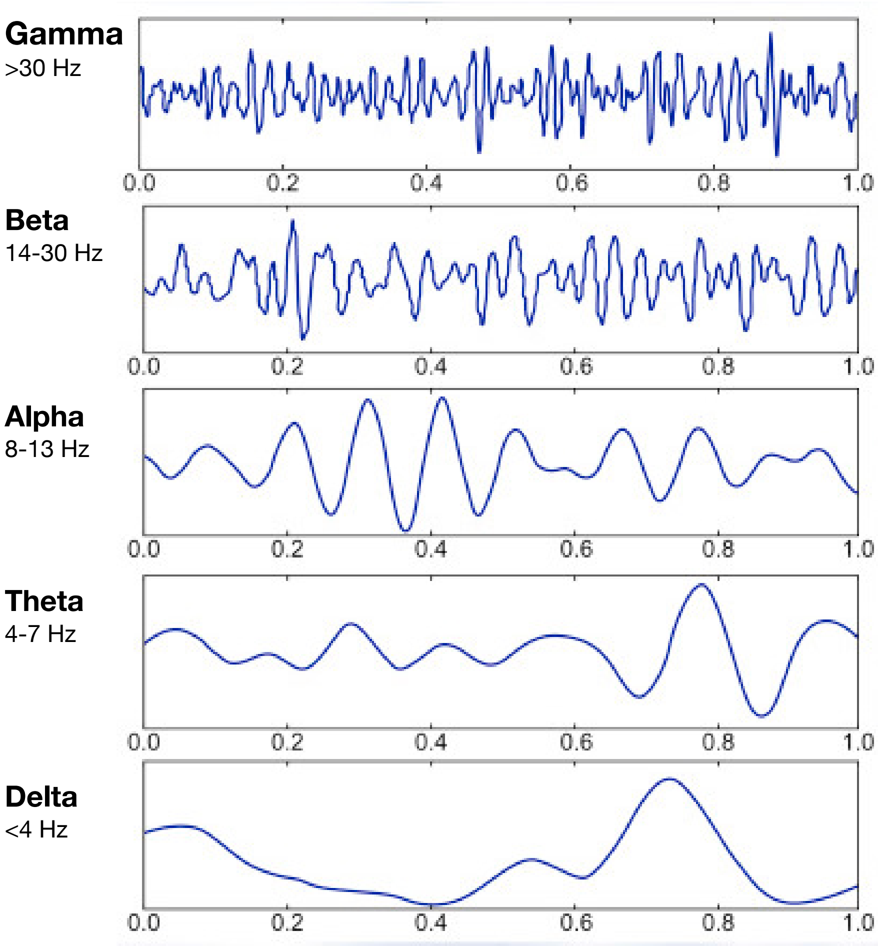

Figure 1.1: The five common frequency waves (Abhang et al., 2016).

The EEG is a method of recording the electrical signals across the cerebral cortex (the top layer of the brain) through the placement of electrodes onto the scalp (Proudfoot et al., 2014). The electrode is simply an electrical conductor, where the electrocortical potentials are connected to amplification equipment (Rowan and Tolunsky, 2003). The EEG is commonly used within the medical domain to help with the diagnosis of epilepsy, as it can show the brain signals changing during an epileptic seizure through spikes in the brainwaves (Sylwester, 2004). It has also been used in non-medical applications such as musical control, where brainwaves are measured and used to control musical parameters (Eaton, 2016).

Modern EEG technology has a very good temporal resolution - the speed at which brainwaves are recorded (van Erp et al., 2012; Eaton, 2016; St. Louis and Frey, 2016). While this is essential for applications that require reliable control, such as for prosthetics (Bright et al., 2016), it can also be an advantage for musical applications as it can allow for the user to control parameters such as pitch (Hinterberger and Baier, 2014) or musical dynamics (Miranda, 2008). Sufficient temporal resolution will also allow for the rapid changes of the brain signals to be easily followed (Hämäläinen et al., 1993). In regard to RQ2, this would allow for adequate real-time mapping that can open up the opportunity for creative mapping techniques, such as the mapping of certain brain frequencies for tempo control.

A downside to the EEG is the relatively poor spatial resolution (van Erp et al., 2012). The spatial resolution represents how precise the EEG is at a specific electrode (St. Louis and Frey, 2016). As the electrodes are measuring the electrical activity on the surface of the scalp, it is extremely difficult to determine whether the signal is being produced within the cortex of the brain or from a deeper region (Proudfoot et al., 2014). A high-quality spatial resolution would be important in a clinical setting, for example, if it were being used to diagnose epileptic seizures. If the seizure is limited in spatial distribution it may not be picked up by the EEG due to the poor quality, which could result in a misdiagnosis (St. Louis and Frey, 2016). However, for use within a BCMI the spatial resolution is not deemed as much of an issue. It is not necessary to know exactly whether the signal is coming from the cortex or from a deeper region within the brain, as long as we know how to deal with the signal. Emmerson (2018) also states that the EEG is the most viable and practical method of detecting brain signals for a BCMI. In terms of practicality, the EEG equipment is portable and small in size, as it often consists of a head cap for the electrode placements, electrodes, and portable interfaces. The cost of a consumer-level EEG headset can be inexpensive, making it more available and accessible to users (Eaton, 2016).

Another method of recording brain activity is the *magnetoencephalography* (MEG), introduced into the scientific community in 1972 (Braeutigam, 2013). This method records the magnetic fields that are generated by the brain (Sato and Smith, 1985) and in a similar way to the EEG, is often used in clinical settings for diagnosing epilepsy. The MEG can measure the weaker signals in the brain regions that would not necessarily be picked up using the EEG (Hämäläinen et al., 1993). Musical studies with the MEG have been limited to passive listening, since the equipment has to be installed within magnetically shielded rooms to reduce any external magnetic noise (Singh, 2014; Chacon-Castano et al., 2017). Passive listening involves observing the users responses from listening to music, as oppose to creating music. The analysis of the MEG involves enormous datasets that require a vast amount of computer processing power and a considerable amount of complex data analysis (Proudfoot et al., 2014). Regarding RQ1, this would present technical challenges for a user who may not be familiar with data analysis, such as a musician.

The MEG has a very similar temporal resolution to the EEG (Singh, 2014), however, it can provide a greater spatial resolution in comparison to the EEG as each sensor is independent and less sensitive to muscle interference (Chacon-Castano et al., 2017). This does not mean that the signal is free from interference, as electromagnetic signals can also be generated by movement of the head, blinking of the eyes, or muscle movement (Proudfoot et al., 2014). A positive to the MEG is that the magnetic fields which are generated by the brain can pass through the skull and scalp relatively unaltered (Proudfoot et al., 2014), whereas the electrical activity struggles with the EEG (Singh 2014).

The equipment that the MEG uses to measure the magnetic fields in the brain includes magnetometer coils, superconducting sensors and a large MEG scanner (Proudfoot et al., 2014). To record the neuromagnetic signals in the brain, the MEG scanner contains magnetometer coils and superconducting sensors that have to be cooled to a specific temperature (Proudfoot et al., 2014). These sit inside a very large helmet-shaped container which is placed onto the users head (Proudfoot et al., 2014). The user of the MEG must also limit body movement, while the head must be constrained in the helmet (Chacon-Castano et al., 2017). In relation to RQ1, this method would cause many technical issues due to the limitations of the equipment. The equipment is certainly not portable due to it being required to stay in a magnetically shielded room, which would make it unsuitable for use within a BCMI. In addition to this, the MEG scanner is also extremely expensive, making it impractical to use with creative applications (Chacon-Castano et al., 2017).

Lastly, the *functional magnetic resonance imaging* (fMRI) is another method of measuring brain activity. It does this by detecting changes in blood oxygenation and blood flow in response to cognitive tasks (van Erp et al., 2012). During a cognitive task, if a part of the brain receives slightly more oxygenated blood, then it means that a particular part of the brain is more active than others (Bunge and Souza, 2009). This is used in the medical domain for learning about how a brain is functioning and to assess how risky brain surgery may be (Proudfoot et al., 2014). Much like the MEG in terms of musical applications, the fMRI is often used for passive listening (Miranda et al., 2008).

The temporal resolution of the fMRI is relatively poor, with 5-8 seconds being the time between two data points that can be distinguished (Proudfoot et al., 2014). This poor time-resolution would make this method impractical for use by a system developed as an interactive compositional tool, as it would be unsuitable for real-time control over musical parameters (Eaton, 2016). However, the spatial resolution is far more superior compared to the MEG and EEG, meaning that activity within the brain can be localised with millimetre precision and can still be distinguished from each other (Proudfoot et al., 2014). Bunge and Souza (2009) state that because of the poor temporal resolution, the fMRI is often used alongside the EEG for clinical purposes. The equipment that the fMRI requires is an MRI scanner, which is a large cylindrical tube with a very powerful electro-magnet. The scanner requires the person to lay down and restrict movement. Unfortunately, much like the MEG scanner, the MRI scanner is extremely bulky and not portable, which would not be practical for use with a BCMI (Miranda and Castet, 2014). Miranda and Castet (2014) also state that fMRI scanners produce noise during scanning, which would cause disruption for a musical application.

Upon discussing these methods, it is now necessary to consider the research aims and questions and determine which would be the most suitable method to be used for the BCMI. The first aim of this thesis is to determine an appropriate method that can be used to develop a BCMI system. The EEG and MEG are very similar in temporal resolution, which will allow for real-time control over musical parameters. The fMRI has a much slower temporal resolution, which would mean that real-time control would not be applicable. Real-time control over musical parameters have been the popular option amongst current BCMI systems (Eaton, 2016; Eaton and Miranda, 2013; Leslie and Mullen, 2011; Miranda, 2006) as it can allow for real-time communication between the performer and the audience, or real-time communication between the composer and the musicians. In addition to this, for a system being used as an interactive compositional tool, it is essential to have real-time control over musical parameters.

The EEG has successfully been used for real-time control over musical parameters such as dynamics (Miranda, 2010) and tempo (Daly et al., 2014), whereas the MEG has only been used for passive listening due to size and practicality of the equipment (Chacon-Castano et al., 2017). The MEG would be suitable if one wanted to measure the user's brainwaves in response to auditory stimuli. However, it is important to remember that the MEG equipment needs to be installed in a magnetically shielded room. This makes the method impractical for any BCMI system used for real-time control over creative applications.

In terms of practicality and portability, the fMRI and MEG equipment are both extremely large and are not suitable methods outside of laboratory conditions due to this. However, the EEG equipment has no restrictions on being used outside of a laboratory-controlled environment; it is also portable, making it suitable for compositional purposes. In addition to this, the EEG is suitable for real-time control, allowing for an interactive compositional tool to be developed. Due to the limitations that the fMRI and MEG methods present, the EEG would be the most practical and suitable approach for measuring brain signals for musical control.

1.2. The electroencephalogram (EEG)

The electroencephalogram (EEG) uses electrodes to measure the electrical signals from within the cerebral cortex of the brain. The EEG either uses dry electrodes or wet electrodes. Dry electrodes go directly on the surface of the scalp with no solution applied to them, whereas wet electrodes require a saline solution or gel to be applied to increase the contact between them and the scalp (Rowen and Tolunsky, 2003).

The electrodes are placed on the scalp in a montage, with different montages used for various purposes (St. Louis and Frey, 2016). A montage measures the EEG alongside a ground and reference electrode (Eaton, 2016), and are divided into two types: bipolar and referential montages, which are used routinely in EEG recordings (Acharya and Acharya, 2019). A bipolar montage means that there are two electrodes for one channel (St. Louis and Frey, 2016), indicating that a second electrode can be used as a reference for signal comparison (Eaton, 2016). A referential montage means that there is one reference electrode for all channels (Acharya and Acharya, 2019). These montages and placement of electrodes follow the international 10-20 system of electrode placement (Figure 1.2). The 10-20 system is an internationally recognised method that was developed to maintain standardised testing methods and to ensure that subjects outcomes could be reproduced (Khazi et al., 2012). This also ensures that the electrode spacing is equal on the scalp.
The 10-20 system identifies 19 locations on the scalp which all relate in a proportional way to four reference points: the bridge of the nose (the nasion), the bump at the back of the head above the neck (the inion), and the left and right preauricular points (above the cheekbone just in front of the ear) (Empson, 1986). The locations are labelled as followed:

frontal (F), frontal-polar (Fp), temporal (T), central (C), parietal (P), and occipital (O) (Rojas et al., 2018). (Z) refers to an electrode that is placed in the midline section of the skull and are often used as reference points. The numbers refer to the left and right side of the brain, with the odd numbers referring to the left and the even numbers referring to the right (Rojas et al., 2018). The (A) refers to the prominent bone found just behind the ear. Three electrodes are the minimum number that are necessary for a suitable connection, with the electrodes placed on the forehead as it is one each hemisphere of the brain, and a reference electrode in the centre (Straebel and Thoben, 2014). Certain frequencies are better recorded in particular regions of the brain, and thus, it will be required to identify the frequencies used for the development of this BCMI, which will be addressed further on in this chapter.

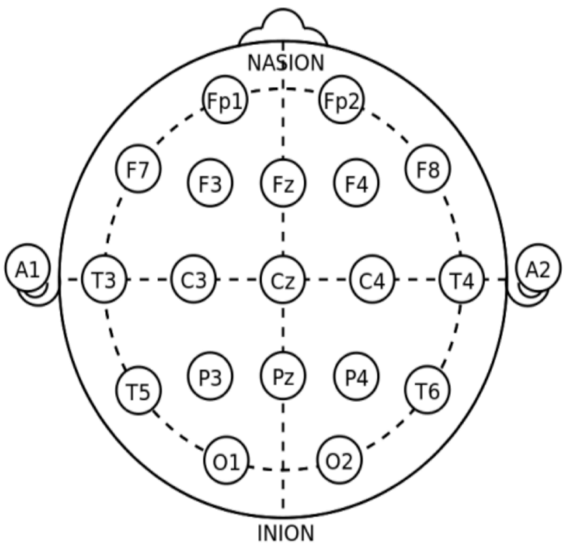

Figure 1.2: The international 10-20 system of electrode placement (Khazi et al. 2012).

When the electrode captures the electrical fields within the brain and records it, this produces raw EEG data. Raw EEG data is a complex wave form that consists of brainwave activity, the electrical activity of muscle movement, and nearby electrical sources (Iscan et al., 2011). Any unwanted signals of muscle movement or electrical interference can be removed using signal processing techniques such as bandpass filtering (Straebel and Thoben, 2014). For example, interference from nearby electrical equipment can cause electrical noise of 50 Hz or more. A lowpass filter that filters out any signal higher than 49 Hz can eliminate this electrical noise without losing important frequency components of the EEG signal (Usakli, 2010). It is important to note that the electrical fields are extremely faint when they are recorded as they must pass through muscle tissue, membrane, scalp, and hair before reaching the electrodes (Eaton, 2016). Due to this, the signal requires amplification before it can be used with a BCMI (Eaton, 2016; Emmerson, 2018). Furthermore, interference from muscle artefacts, hair, heart, or static sources can impact the ability to interpret the EEG data adequately (Rowen and Tolunsky, 2003), with non-invasive methods being more susceptible to unwanted artefact interference (Straebel and Thoben, 2014).

A digital EEG system is required to convert the waveform using analogue-to-digital conversion (ADC) (Casson and Rodriguez-Villegas, 2008). During this process, an analogue signal (which are the EEG signals) is converted into a digital signal so it can be stored in a computer for processing (Al-Fahoum and Al-Fraihat, 2014). This is accomplished by sampling the signal at discrete points in time (Casson and Rodriguez-Villegas, 2008). The sampling rates typically occur at 256-512 Hz (Miranda and Castet, 2014). For example, 256 Hz sampling rates means that one-second of EEG will have 256 data points. This produces a time-based signal (Figure 1.3). To transform a time domain to a frequency domain, the fundamental technique, Fourier transform (FT) is used. One can window the data and perform a FT to view the signal as a set of frequency bins with respective magnitudes. An FT is a method that employs mathematical measures to the EEG analysis and to decompose a waveform into sinusoids (Al-Fahoum and Al-Fraihat, 2014). This allows for one to break up the raw EEG signal into its respective frequency bands (Figure 1.4).

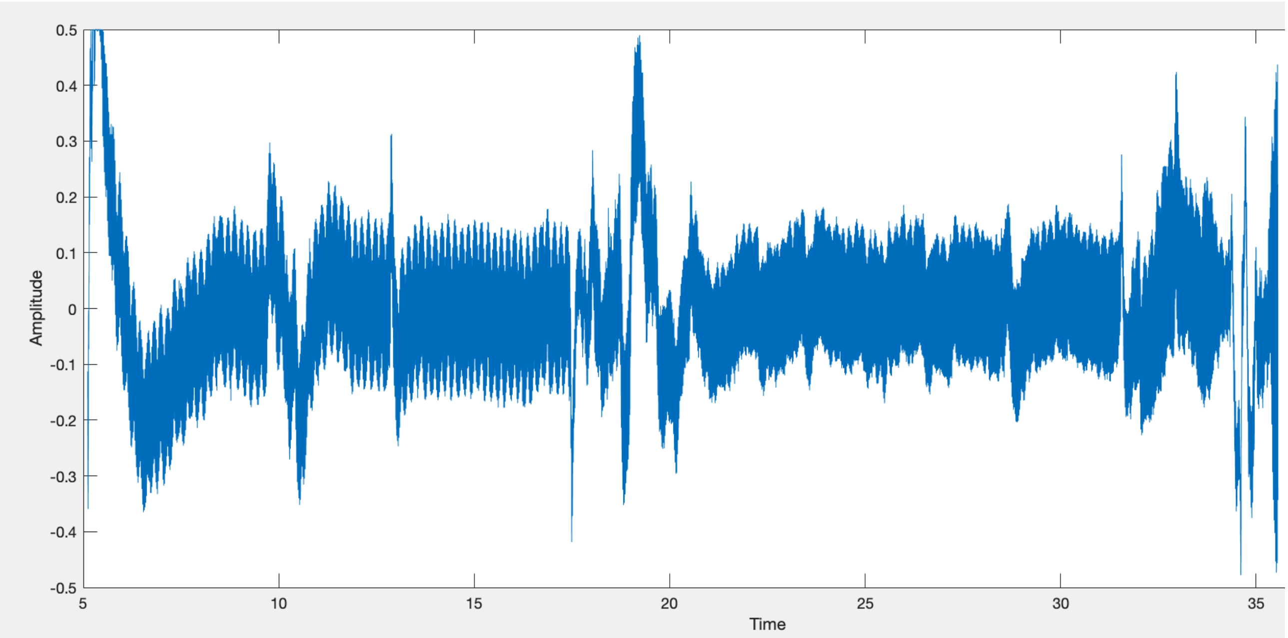

Figure 1.3: Time-domain signal.

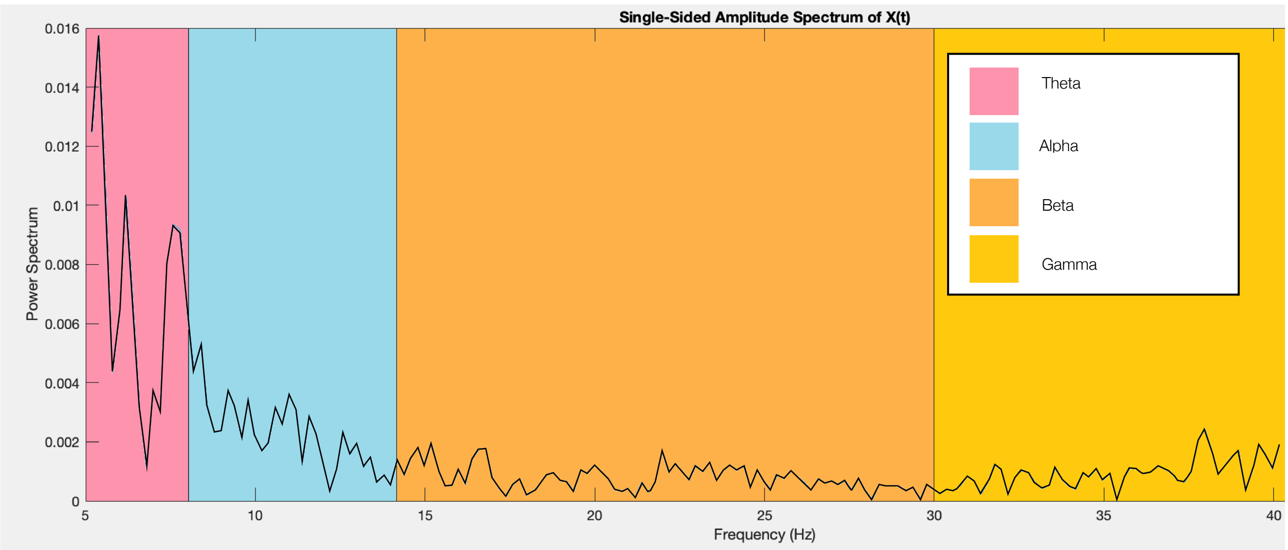

Figure 1.4: Frequency domain spectrum from raw EEG signal.

The EEG signal has different frequency bands, which are defined by the frequency of the waves: delta (less than 4 Hz); theta (4-8 Hz); alpha (8-12 Hz); beta (13-30 Hz) and gamma (30-80 Hz) (Table 1.1) (Iscan et al., 2011). These frequency bands can be extracted from the raw EEG data using a band-pass filter. To determine the appropriate frequencies to measure for musical control, the frequency bands must be considered in terms of the research questions.

Frequency Band	Range of Frequency	Associated Mental State
Delta	< 4 Hz	Deep sleep
Theta	4 - 7 Hz	Drowsiness
Alpha	8 - 13 Hz	Relaxed, waking state with eyes closed
Beta	14 - 30 Hz	Alert, waking state with eyes open
Gamma	> 30 Hz	Extremely anxious

Table 1.1: The frequency bands and their associated mental state (Eaton, 2016, p.48)

The delta wave is the slowest recorded brain wave (Abhang et al., 2016) and is prominent when a person is in deep sleep (Malik and Amin, 2017). It is located within the frontal, temporal, and occipital region of the brain (Rowen and Tolunsky, 2003) and is high in amplitude making it easier to detect with the EEG (Malik and Amin, 2017). Although the delta wave is more pronounced during deep sleep, it has still been used in BCMI systems such as Ouzounian et al. (2011) system. Ouzounian et al. (2011) developed a BCMI system where four performers controlled music using their alpha and delta waves. The delta waves were mapped to the timbre of the tones. While Ouzounian et al. (2011) state that the delta waves are not completely controllable, the reason they used them were to effectively communicate the act of watching the performers sleep to an audience (Eaton and Miranda, 2013). As the delta wave is only prominent during deep sleep, it would not be a viable option to use for the BCMI system for this thesis as the user would not have any control over their delta waves. Regarding RQ2, this would severely limit the control that the user could have over specific musical parameters, and would therefore not provide an adequate interactive compositional tool.

The theta wave can be present during drowsiness and wakefulness (Abhang et al., 2016), although Rowan and Tolunsky (2003) state that it may also be completely absent. This would make it extremely challenging to integrate this frequency wave into the compositional process, as it may not be present in every user. This frequency wave has not been used in many BCMIs for musical control, although Daly et al. (2016) recorded a participant's theta wave (alongside other frequency waves) as part of an affective state detection system. Multiple pieces of music were generated depending on the user's affective state (Daly et al., 2016). Unfortunately, the theta wave would not be suitable for use with a BCMI developed for compositional purposes as it would not be reliable enough due to the fact that it may be completely absent from the user. In addition to this, the user would have to be in a drowsy and wakeful state making it impractical for use over control.

The alpha wave is one of two most common used frequency waves, along with the beta wave (Giraldo and Ramirez, 2003). The alpha wave is present in the majority of people and is one of the easiest waves to detect (Giraldo and Ramirez, 2003). Although Hundia (2015) stated that the alpha wave has a very low amplitude, Rosenboom and Paul (1986) commented that Rosenboom successfully used the alpha wave in his composition. This was because they were easiest to detect when recording brain signals on the surface of the scalp compared to the other waves (Rosenboom and Paul, 1986). The alpha wave has become popular for control because the wave can be voluntarily controlled with the opening and closing of the eyes (Hundia, 2015). When the participant has their eyes closed and are relaxed, the alpha wave has a higher amplitude. When the participant opens their eyes, there is a decrease in the amplitude (Levicán et al., 2017). In terms of RQ1, using the alpha wave for musical control would allow for creativity, especially as the increase and decrease in amplitude can be voluntarily controlled. In addition to this, the alpha wave is easy to detect which makes it suitable to use with a BCMI that is developed as an interactive compositional tool.

The beta wave is often present when a person is in an alert waking state and is focused (Wang et al., 2016). Similar to the alpha wave, it is also low in amplitude (Abhang et al., 2016), meaning that a lot of amplification equipment is required. However, this has not stopped it from being used for musical applications. For example, Miranda's (2008) BCMI system used both the alpha and beta waves for musical control with success. In terms of RQ1, the beta wave would allow for creative mapping techniques to be used, such as mapping the tempo to the amplitude of the frequency. Having said that, Giraldo and Ramirez (2003) stated that the alpha and beta waves are the two easiest frequencies to detect, which, much like the alpha wave, would make it suitable to use with a BCMI.

The gamma wave has not been as widely studied compared to other brain waves (Malik and Amin, 2017), even though they are considered to be the fastest brain activity (Abhang et al., 2016). They are small in amplitude and contain high interference from muscle artefacts (Malik and Amin, 2017). Gamma waves are present during deep sleep and can also be evoked by intense attention and visual stimuli (Abhang et al., 2016). As the gamma waves are not always present in the user, it would not be appropriate for a BCMI system. Additionally, the user is required to be in deep sleep which would mean they cannot consciously control their gamma wave and subsequently any musical aspects.

While it is certainly possible to utilise all five frequency bands for purpose of control, this may not be useful for musical applications. Hinterberger and Baier (2004) utilised the five frequency bands for a BCMI and recorded a low accuracy rate which they reported was due to the monitoring of all frequency bands at once. Considering the research questions and the aims of the system, it has been concluded that the alpha and beta waves would be the most practical frequency bands to use as they will allow for some level of musical control and subsequently interaction with musical aspects of a composition. In addition to this, using multiple frequency bands will allow for more creative mapping techniques to be implemented in the system. There have been many studies with BCMI systems that have used both the alpha and beta waves for numerous experiments, each proving successful (Leslie and Mullen, 2001; Miranda et al., 2011; Mullen et al., 2011; Daly et al., 2018; Levican et al., 2019).

1.2.1. Alpha waves

Alpha waves are sinusoid-like neuronal oscillations that are caused by neurological activity within the brain (Straebel and Thoben, 2014). Hans Berger, the psychiatrist who developed the EEG, discovered the alpha wave in the 1920s (Miranda, 2006). The discovered alpha wave was running at 10 cycles per second (Hz) (Empson, 1986). Now, the alpha wave is said to be between 8 Hz and 12 Hz (Iscan et al., 2011). Empson (1986) states that Berger also discovered that the alpha wave disappeared if the eyes were opened and the person solved mental arithmetic or a similar mental task. However, this discovery did not gain recognition until the 1960s, when Joe Kamiya published an article on his study about increasing the amplitude of the alpha wave by closing the eyes (Straebel and Thoben, 2014). This closing of the eyes causes a fluctuation in the alpha wave, which can be seen in the EEG activity as a rise in amplitude from an increased voltage. When the user opens their eyes, the amplitude reduces and the voltage decreases.

Levicán et al. (2017) study used the fluctuation of the alpha wave to control the overall sound of a melody, with a decrease in the dynamics when the user went from a relaxed state to a more alert state. This allowed for the user to feel in control of the dynamics. Although Levicán et al. (2017) study was successful, the representation of being in a relaxed state with an increase in dynamics seems almost counter-active. As Juslin and Sloboda (2011) determined in a study, those who were relaxing preferred quieter and slower music. Due to this, it would be more appropriate to utilise the relaxed state to prompt a relaxing musical parameter such as a lower velocity or a slower tempo. This would help the user maintain a relaxed state. In terms of both RQ1 and RQ2, the fluctuation of the alpha wave can provide interesting mapping techniques that will provide creative opportunities to the user. One idea could be to use the fluctuation of the alpha wave to control the note velocity of a composition. Note velocity is how light or hard a key is pressed, something which could aid the structure of the composition.

The alpha wave can be recorded by the EEG at the occipital region (Empson, 1986) or the frontal region of the brain (Lucier, 1964). Lucier (1964) performed his piece *Music for Solo*

Performer with the electrodes located at the frontal region of the brain, one on either side of his forehead and one for reference, thus using three electrodes. The minimum number of electrodes that can be used at one time are three (Miranda et al., 2011). The more electrodes that are used, the more complicated the data can become, which may cause confusion to a musician using this system as a compositional tool. It is therefore important to consider where the beta wave can be recorded from to ensure that the minimum amount of electrodes for this system can be used.

1.2.2. Beta waves

The beta wave has a rhythmic frequency of 13 Hz to 30 Hz and was the second waveform to be discovered by Hans Berger. It has a larger amplitude and slower frequency wave compared to the alpha wave (Rowen and Tolunsky, 2003). Rowen and Tolunsky (2003) state that the beta wave is often present in the majority of people when they are in a normal, alert, waking state and engaging their mind on a task. In addition, Levicán et al. (2017) states that the beta wave can be present when a person is moving. Initially, any wave above 13 Hz were referred to as the beta wave, however it later became clear to divide the waves within the 13 Hz-30 Hz into two bands: low beta (13-21 Hz) and high beta (21-30 Hz) (Kropotov, 2016). Low beta became associated with quiet, focused concentration and performance, whereas high beta became associated with stress, anxiety, and high energy (Abhang et al., 2016). Kropotov (2016) commented that this is because of the differences in reactivity to tasks. Taking into consideration RQ1, the beta wave being split into two bands could be used to represent the tempo of a composition, with the low beta representing a slow tempo, and the high beta representing a fast tempo. However, this could also cause additional technical challenges to a musician who would not be familiar with this technology.

The beta wave is often found in the frontal or central region of the cortex (Empson, 1986; Kropotov, 2009), with Satapathy et al. (2019) stating that it is most evident in the frontal region. Zheng and Lu (2015) recorded the beta waves using the positions Fp1, Fp2 and a ground electrode at FpZ, with a high accuracy rate. In addition to this, Eaton (2016) recorded the beta wave, alongside the alpha wave, for a BCMI system designed for a live performance environment. The electrodes used were placed across the frontal-polar region of the brain, in locations A3, F3, A4 and F4. This electrode montage successfully recorded both the alpha and beta waves simultaneously with a very good accuracy rate (Eaton, 2016).

1.3. Introduction to the brain-computer interface

Before discussing the BCMI, it is important to address the brain-computer interface (BCI), the predecessor of the BCMI. The BCI is a system that allows for communication or control of a computer using the human brainwaves (Eaton, 2016). While Hans Berger had successfully discovered a method of recording the brain signals, it was Computer Scientist Jacques Vidal who, in 1973, published the idea of using brain signals with a computer for the purpose of control (Leslie and Mullen, 2011; Vidal, 1973). The BCI is commonly used within the medical domain, providing an alternative communication medium for those with motor disabilities (Miranda et al., 2011).

An example of it being used within the medical domain is Rebsamen et al. (2007) BCI that allows for a completely paralysed patient to control a wheelchair around a hospital or office. This BCI uses the P300 technique; a natural, involuntary response to frequency stimuli (Rebsamen et al., 2007). The response is seen as a brainwave spike (also called a potential) that occurs at approximately 300 milliseconds after the onset of the stimuli (Eaton, 2016). This provides the BCI with an ‘oddball paradigm’ where a random sequence of stimuli is presented, but only one stimulus will be of interest (Rebsamen et al., 2007). This system requires the user to select a flashing icon by focusing their gaze on it; the icons are associated with movement options for the wheelchair. As this is used for medical purposes, accuracy would be of upmost importance as it must be safe for the patient to use (Fadzal et al., 2011). However, for creative applications, accuracy would not be as important. While it is desirable to have a fully controllable and accurate system, this will not be the case due to limitations of technology (Eaton, 2016). From a creative perspective, inaccuracy may enhance the composition in a way that the user was not predicting.

Within the past few years, the BCI has expanded from solely being used within the medical domain to include non-medical applications such as gaming, virtual reality (VR) and musical control (Van Erp et al., 2012). While Van Erp et al. (2012) states that non-medical BCIs are still in very early development, Lécuyer et al. (2008) mentions that BCIs provide suitable interaction devices to be used with VR applications and video games. Current BCI systems for VR gaming allow users to change camera positions using techniques such as motor imagery (MI) or steady-state visual evoked potentials (SSVEP) (Lécuyer et al., 2008).

Motor imagery (MI) is a technique used with the EEG. It allows the user to imagine a physical movement such as lifting their right arm whilst the system monitors for any differences that occur in the brainwave patterns (Eaton, 2016). These differences are then used for control. SSVEP is also a technique used with the EEG and is known as an event related potential (ERP), where small voltages are generated in the brain in response to stimuli and are time-locked to an event (Sur and Sinha, 2009; Eaton, 2016). The stimuli are repeated visual stimulation at specific frequencies, which then generates the electrical activity that is recorded by the EEG (Eaton, 2016). Additionally, the SSVEP is said to allow for precise control (Eaton and Miranda, 2013). As stated by Lécuyer et al. (2008), these BCIs can only provide the user with one to three commands associated with a task. An example of BCI technology with a VR video game is Lalor et al. (2004) *MindBalance,* where the BCI was used to interact with a virtual world. The BCI used SSVEP and allowed for the player of the game to control a character walking across a tightrope. In a game-like situation, the accuracy of the system would be important because it could cause frustration to the user if the control commands were incorrect. A lot of BCIs that are developed for VR video games opt for using techniques such as MI and SSVEP as it allows the user to gain explicit control (Eaton, 2016).

BCI systems are an excellent control medium for those with physical disabilities; van Erp et al. (2012) states that users with full muscular control will not benefit from using these systems in comparison to those who lack muscular control. This is because the BCI lacks the accuracy and bandwidth to compete with a computer mouse or keyboard. However, as stated above, accuracy is less of an importance when being used for creative applications. In addition to this, the use of this technology creates many possibilities which outweigh the importance for accuracy.

1.4. Introduction to the brain-computer music interface

Similar to the BCI, the brain-computer music interface (BCMI) is a system that allows for communication and control over musical parameters. The BCMI can be used for musical composition (Miranda and Brouse, 2005), musical performance (Miranda and Eaton, 2013), or more specifically, a musical system developed for those with motor disabilities (Miranda et al., 2011). Although the term BCMI was only coined in 2006 (Miranda, 2006), it is widely accepted across literature that the initial development of a BCMI system was in the 1960s, when composer Alvin Lucier developed a composition using his brainwaves (Lucier, 1976; Miranda, 2006; Daly et al., 2014; Eaton, 2016). Lucier recorded his alpha waves using electrodes placed on his forehead and scalp, which were then connected to loudspeakers placed near or inside percussion instruments. This caused the instruments to vibrate and thus, creating *Music for Solo Performer* (Lucier, 1976). The incorporation of brainwaves and musical composing sparked ideas from experimental composers, who began to collaborate with engineers in order to create new forms of music (Forucci, 2018).

As discussed in the chapter above, the EEG is the most commonly used method to record brain signals for use within a BCMI (Eaton, 2016). As we know that brainwaves can be used to create music (Lucier, 1976), there are also multiple techniques that can be used to control the EEG signals such as the SSVEP, MI and P300. An example of the SSVEP being used with a BCMI is Miranda et al. (2011) SSVEP-based BCMI for a patient with physical disabilities. This system used the technique for the generation of a melody, and control over musical sequences. A total of four images were displayed on a computer screen which each represented a different musical instrument and a sequence of notes (Miranda et al., 2011). Each image would flash at different frequencies, so when the user gazes at one of those images, that image will be selected and implemented (Eaton and

Miranda, 2013). The notes that form the melody are produced from the varying control signal prior to the selection of the images. The user can choose 6 notes which are selected through the intensity of their gaze (Eaton and Miranda, 2013). This system proved very successful and reliable, although it is important to note that to be able to use a system that incorporates the SSVEP, a lot of training and knowledge would be required (Miranda et al., 2011). In regard to RQ1 this would present many technical challenges for a musician, such as the requirement of understanding hard-coding software. For a musician who is using this technology to integrate it into a system for a compositional tool, they would not have an understanding of programming languages or signal processing mathematics. Therefore, this method would not be a suitable option for a BCMI developed as an interactive compositional tool.

Daly et al. (2014) BCMI system applied MI for the modification of tempo for dynamically generated music. The participants of this system were able to increase the tempo of the music by imagining they are clenching their fists, and decrease the tempo by relaxing (Daly et al., 2014). One of the downsides to using MI, as reported by Daly et al. (2014), is that accuracy can vary from test to test and the reliability is not consistent. Despite this, Daly et al. (2014) also stated that the accuracy would increase over sessions. This suggests that, through continuous practice, the user would be able to learn to control the tempo. The tempo of the music was mapped to the user's alpha wave, which was then inverted. Therefore, when the user relaxed and their alpha wave amplitude increases, the tempo will decrease. The electrodes were placed in the frontal, central, temporal, and parietal regions of the brain (Daly et al., 2014). While this technique could prove beneficial to those with motor disabilities for therapeutic purposes, there are techniques that would be more useful in a BCMI that has been developed for compositional purposes.

Pinegger et al. (2017) developed a BCMI system that incorporated both the SSVEP and P300 technique. This system focused on allowing the user to select an individual note to form a composition using the notation software, *MuseScore*. The system has a 3 x 6 matrix containing the options of “compose,” “new,” “save,” and “open”. When the user selects “compose," the matrix will automatically switch to the 6 x 6 composing grid, prompting *MuseScore* to open. The 6 x 6 matrix includes common musical elements that are all available in *MuseScore,* such as note lengths, accidentals, and rests. To select a note, the user is required to focus their gaze at the note they wish to select, and then they can choose the note pitch and any accidentals (Pinegger et al., 2017). This system aims to allow for one to compose music note-by-note using their brainwaves. While this system would be suitable for those with motor disabilities, as van Erp et al. (2012) stated, those with full muscular control would not benefit from such system. This is because a BCMI system such as Pinegger et al. (2017) is useful in replacement of a keyboard and mouse or pen and paper; providing those with motor disabilities the option to compose music. However, for those with full muscular control, this system does not offer any new compositional tools that would aid in the process of music making.

Eaton (2016) states that each BCMI system can differ in terms of application, cost, signal processing, data handling, and mappings. Despite this, Eaton (2016) identifies five elements that all BCMI systems are likely to consist of. Firstly, a BCMI may include auditory or visual stimuli. Secondly, a BCMI will consist of the electrodes placed on the scalp and the processing of the EEG signals (including the amplification of electrical signal, data extraction and filtering of unwanted signals). Lastly, a BCMI will consist of a transformation algorithm, which maps non-musical information to the musical engine; the receiver of the commands. This is often a MIDI instrument or a musical software. These elements will be explored further in chapter three. Alongside these elements, the BCMI also falls into three categories with how music is generated: sonification, musification and BCI control (Eaton, 2016).

Chapter Two: Exploring Composition within a BCMI

Overview

This chapter explores composition within a BCMI to determine the most appropriate method to be used to integrate this technology into the compositional process. Current BCMI systems can allow for a user to change the structure of a piece or alter the musical tempo via their brainwaves. These changes can represent the user's current mood or emotion. This chapter will feature a survey of approaches to harnessing brainwaves in music, surveying multiple BCMI systems against criteria. The aim of this chapter is to address both RQ1 and RQ2 to form a clear direction that the system will take.

2.1 Survey of approaches to harnessing brainwaves in music

There are multiple approaches to harnessing brainwaves for musical purposes. It has been stated by Eaton (2016) that the three categories BCMI systems fall into are sonification, musification and BCI control. Sonification is a technique which essentially makes data audible (Kramer et al., 2010). This has been used for the mapping of numerical data such as weather reports or stock market data to create an audio representation from it (Dean, 2009). For example, a stream of data could be mapped to pitch to allow for a listener to understand fluctuations aurally. Musification has been defined as the musical representation of data (Coop, 2016). While this technique sounds very similar to sonification, the distinction between them both is that musification follows a series of various rules which are used to create a musical composition from the data (Nam et al., 2018). Musification also includes elements of tonality and modal scales, taking advantage of musical features (Coop, 2016). Lastly, BCI control is a technique where the EEG signals are used to command a musical application (Forteza Crespí, 2013). Essentially, BCI control would allow for active control over musical parameters, which for greater accuracy, may also use external stimuli to generate control (Eaton, 2016).

These three approaches to harnessing brainwaves each come with positives and negatives. The aim is to discuss these approaches alongside current BCMI systems and determine which approach would be best suited for a BCMI developed as an interactive compositional tool. Therefore, the approaches will be surveyed according to the two criteria as followed:

1) Which approach offers suitable opportunities of harnessing EEG technology for a musical composition?
2) Which approach would allow for creative mapping techniques to be implemented in a BCMI that is to be used as an interactive compositional tool?

The criteria in place is to support both research questions. Criteria 1 supports RQ1, through aiming to define which approach would offer the appropriate opportunity of harnessing EEG technology for compositional purposes. Criteria 2 supports RQ2 in terms of the creative mapping techniques that can be adopted to integrate brainwaves into the compositional process.

2.1.1. Sonification

Sonification is when sound, such as pitch or amplitude, is mapped to a dataset. One of the earliest uses of sonification is the Geiger counter; a radiation detecting device developed in 1908 (Garner, 2017). This device transformed each detected ionisation event into a single click (Garner, 2017). The use of sonification for musical purposes has been described as 'artistic sonification' (Straebel and Thoben, 2014).

Eaton (2016) expresses that sonification is often used for monitoring EEG behaviour in medical situations as opposed to artistic applications. An example of using sonification for medical purposes would be Baier et al. (2007) system, which used sonification for the purpose of generating sound samples from the rhythm of epileptic disorders. They describe a method to generate event-based rhythms from multi-channel EEG and map the events of interest to digital synthesis parameters in a music software (Baier et al., 2007; Eaton, 2016). Their focus for this development is not for musical purposes, but to aid the distinction between normal and abnormal rhythms in patients. Nonetheless, this system incorporates parameters such as note length, volume, and pitch, all essential to a musical note. Essentially, by linking expected EEG rhythms to synthesis parameters such as amplitude modulation and harmonic content, a sonified representation of meaningful data can be produced. While this system may provide some interesting musical results, evidently, the participant would not have any control over the musical outcome.

In contrast to Baier et al. (2007) system, Hinterberger and Baier (2004) developed a system with the aim to create an interaction loop, where the human EEG waves provided auditory feedback in real time to the participant whose brainwaves fed the sonification. This system, named *POSER (Parametric Orchestral Sonification of EEG in Real-Time),* applied musical mappings to serve real-time analysis of the changes in bandwidth frequencies. Parametric sonification is one of several techniques that can be used for auditory presentation of data. Hinterberger and Baier (2004) extracted data from the five common frequency bands of a participant and assigned them to voices of a MIDI device. Each voice was assigned to one of 16 MIDI channels, with each channel having three parameters: one for an instrument, one for the volume and one for the balance. In addition to this, each voice had auditory parameters containing the timing, pitch, and velocity. The EEG data was used to modulate either the pitch or velocity, or both at the same time. When all instruments were played back at the same time, the dynamics of each individual voice was balanced according to the participants spectral power distribution. Hinterberger and Baier (2004) established that this aided the overall musical shape of the final composition. In addition to this, Hinterberger and Baier (2004) stated that the participants were asked to focus their attention alternately on two difference sounds. The first was to focus on the rhythmic vibraphone that was being represented by the alpha, theta and gamma waves, and the second was to focus their attention on the smoother sounds which were being represented by the delta and beta waves. It was reported that the participants were able to self-regulate EEG parameters with orchestral feedback (Hinterberger and Baier, 2004). Furthermore, Hinterberger and Baier (2004) also stated that the aim of this system will be used to detect specific motifs in the continuous sound patterns that can be related to a mental state. This will mean that the user will not have control of the musical outcome.

In respect to the first criteria for this survey, Hinterberger and Baier's (2004) system offers more opportunities of harnessing EEG technology for compositional purposes in comparison to Baier et al. (2007), although these opportunities are limited. The use of five frequency bands allowed for numerous instruments to be used, alongside musical parameters such as note pitch and velocity. However, as the aim of this system is to detect specific motifs in the continuous sound patterns, this would limit the opportunities that EEG technology could provide for a musical composition. There would be limited control from the user, and the outcome of the music would not be certain. Baier et al. (2007) system focused purely on using this technology to generate sound samples from epileptic disorders, which instantly limits the opportunities of music-making. Additionally, there is no control over the musical outcome, much like Hinterberger and Baier's (2004) system.

In terms of the second criteria, both systems have the capability to provide creative mapping techniques, but not to the extent that would be suitable to be used in a BCMI to create an interactive compositional tool. Hinterberger and Baier (2004) included note pitch and velocity, with dynamics being controlled by the participants spectral power distribution. For a BCMI to be used by a composer as a compositional tool, this system would prevent many technical challenges and a lot of high-end programming, something which a composer would not have knowledge of. Additionally, Baier et al. (2007) system incorporates note length, velocity, and pitch, but the user would not have any control over and would thus not be interacting with the composition.

2.1.2. Musification

Musification is a structure of musical rules that are applied to EEG data (Eaton, 2016). As Eaton (2016) stated, EEG data does not have a time signature or any musical style and is, therefore, required to be intervened by an individual or computational process with musical training. Eaton (2016) also states that musification is suitable for composers wishing to inject their own styles into the translation of EEG.

An example of musification is Miranda and Soucaret's (2008) BCMI system, where EEG electrodes are mapped to musical notes. A total of 14 electrodes are individually associated with a musical note, allowing for an entire octave to be covered. A single note is then played when the respective electrode is most active in the raw EEG data (Eaton, 2016). The association between notes and electrodes can be changed, meaning that various pitches or scales can be used. This allows for musical creativity to be explored, with the composer being able to change the notes of the associated electrodes. The length of a note depends on how long the electrode stays active within a specific pre-set time window. The user of this system would not be able to control each individual electrode, but as the user's data is always representative of their biological state, this could produce interesting and meaningful musical results.

In consideration of the criteria, this system offers suitable opportunities from harnessing EEG technology that would aid a composition, such as note length and pitch change. However, as the user would not be able to specifically choose a desired note, this may cause the composition to have no sense of structure of direction. Nonetheless, the electrodes could be used to only prompt specific notes if certain frequency bands are active. For example, if electrode location F2 is active with the alpha wave, then it prompts a major note; but if electrode F4 is active with the beta waves, then it prompts a minor key. Not only would this be representative of the user's biological state but it would also enable this system to be used as an interactive compositional tool, thus allowing creative mapping techniques to be explored.

Miranda (2010) developed this system further to create the *BCMI-piano;* a BCMI system that uses artificial intelligence (AI) to enable a form of decision making with EEG control. In comparison to Miranda and Soucaret's (2008) BCMI system that triggered musical notes one-by-one, *BCMI-piano* uses the information from the EEG power spectrum analysis to control an intelligent system that composes music online (Miranda, 2010). A generative system composes the music using rules that are extracted from a given example, for instance, features based on the techniques of composers such as Beethoven or Schumann (Eaton, 2016). Each time the system has to produce a bar of music, it observes the power spectrum of the EEG at that precise moment. This subsequently triggers generative music commands that are associated with the most prominent EEG rhythm in the signal. In respect to the criteria, this can provide an exciting creative opportunity for the composer that would allow them to compose using features from composers of their choice.

The amplitude of four bandwidths are monitored for this system, which are delta, beta, alpha, and theta. The information is then played on a MIDI-enabled acoustic piano. If the alpha wave was more prominent, then Schumann-like elements will be generated in the music (Miranda, 2010). If the beta wave was more prominent, then Beethoven-like elements will be generated (Miranda, 2010). This offers the user a level of control, providing they are able to learn how to control their EEG frequency waves. Miranda (2010) also uses Hjorth analysis, which is used in signal processing in the time domain. The parameters that Hjorth analysis uses are activity, mobility, and complexity of the signal. The activity parameter represents the signal power, mobility represents the mean frequency of the power spectrum, and complexity represents the change in frequency. Measures that are read from the Hjorth analysis are employed to modulate the tempo and dynamics of the composition. While this is uncontrollable by the user, the biological state of the user influences the results and thus provides a meaningful level of interactivity within music making.

As for the criteria, this system allows for creative mapping techniques to be implemented by integrating techniques that are used by famous composers. This can include a variety of musical features, such as repetitive phrases, articulation, and key changes. Eaton (2016) states that musification offers interesting mapping opportunities that does not restrict the amount of control a user can provide. If we compare these two systems with the two systems used as examples for sonification, it is clear that this system offers more musical flexibility in what can be achieved. With the ability to include musical rules, musification offers the user the ability to develop a composition based upon their desired structure and form.

2.1.3. BCI control

BCI control is where the EEG signals are used to command a musical application (Forteza Crespí, 2013). This method can either be passive, active, or an incorporation of both. Passive control offers the user to be free from any distractions that active control may use, such as the user's thoughts and attention on stimulus. It has been argued that a downside to passive control is that it does not let the user feel in control (Eaton et al., 2015), however, much like the above systems, the element of the data being representative of the user's biological state allows for meaningful results.

Miranda (2008) developed the *BCMI mixer,* a BCMI that employs the alpha and beta waves for control over the volume of two tracks. The idea of this system is that when prominent alpha waves are detected, the volume of a solo guitar track will increase according to the amplitude of the alpha wave. Similarly, when the system detects prominent beta waves, the volume of a solo piano track will increase according to the amplitude of the beta wave. While this system is only allowing for the user to have control over the volume, the level of control that this offers allows for adequate musical results. A user would be able to, with practice, train themselves to prompt their alpha and beta waves. As mentioned in chapter 1.2, one can prompt their alpha waves by closing their eyes and relaxing, and their beta waves by opening their eyes and focusing on a mental task. This would allow for a level of control, with practice from the user. Miranda (2008) also stated that this system proved successful and produced accurate results where the user was able to control their brainwaves. While this system only offers control over one musical parameter, this could potentially be expanded to incorporate numerous musical parameters, such as utilising the alpha and beta waves to control the tempo.

Another example of BCI control would be Miranda et al. (2011) BCMI system that incorporated the eye gazing technique; steady-state visual evoked potential (SSVEP). This technique requires icons to be displayed on a computer screen that each flash at different frequencies. Specifically, this system used four flashing icons on a screen that were correlating to the frequencies of the relative brainwave that were being measured (Miranda et al., 2011). To select one of the four icons, the user is required to simply gaze at the icon which increases the amplitude of the relative brainwave frequency (Eaton, 2016). Each icon represents a musical command, which are fed back to the musical engine and added to a musical score. Miranda et al. (2011) gave an example into how this system could be used, with a sequence of five musical notes stored in a list, and an index varying from 1 to 5. The user would then be able to slide the index up and down to select one of the five notes. Each of the five bandwidths of power are associated with a corresponding index value. When the signal varies within these bandwidths, the corresponding indices will trigger the associated musical note. This would allow the user to steer the notes by the intensity of their gaze at the specific icon (Miranda et al., 2011). Regarding the criteria, this system only allows the user to choose specific notes and does not necessarily add any new creative aspects to the compositional process. In comparison to Miranda and Soucaret's (2008) BCMI that would select notes that could be representative of the user's biological state, Miranda et al. (2011) system only allows users to select notes from a screen, something which can be achieved without this technology. Additionally, for a system that is to be developed as an interactive compositional tool for musicians, there needs to be consideration into their specific skill set. The use of high level programming languages and signal processing mathematics is not a creative process for a composer and therefore this system would not be suitable.

Eaton and Miranda's (2013) BCMI system, *Mind Trio,* creates an opportunity for two users to compose together to form a game-like situation. This system consists of 96 pre-composed musical phrases that one user can select using the SSVEP technique. The user will subsequently arrange the structure of a musical score. In comparison to Miranda et al. (2011) system, this BCMI does not require the user to input note by note. Instead, this system uses pre-composed phrases. The second user of the system is a musician,

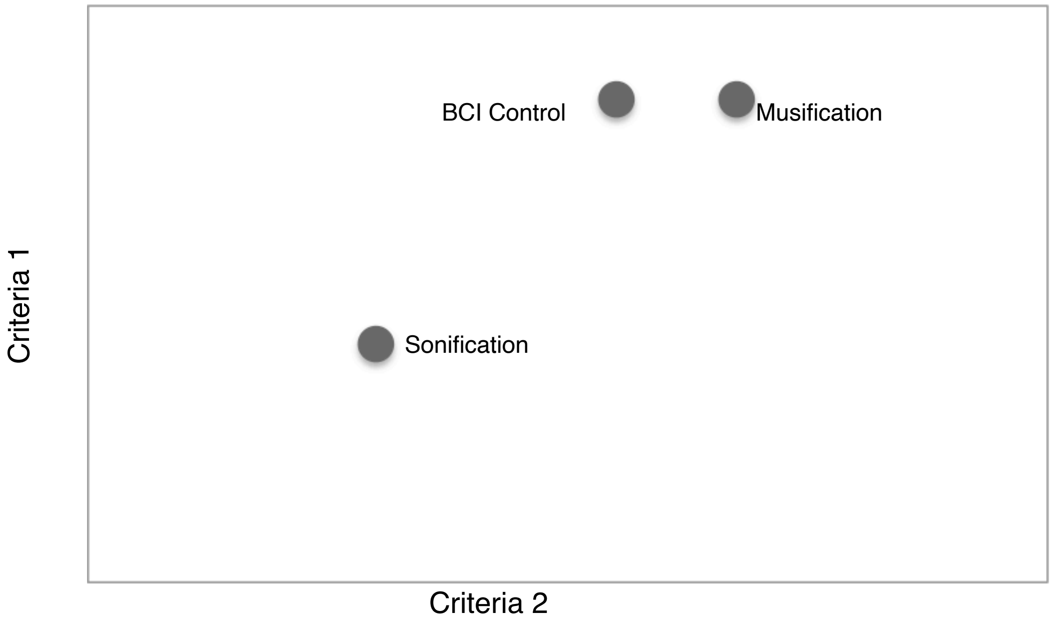

Figure 2.1: Results from the survey; showing criteria 1 (Which approach offers suitable opportunities of harnessing EEG technology for a musical composition?), and criteria 2 (Which approach would allow for creative mapping techniques to be implemented?)

playing back the musical score on an instrument as it displays on the screen. Each line of music contains two bars that equate to approximately 8 seconds of score on the screen. It is essential that the musician playing the score has the ability to read musical segments of a few seconds at once so the tempo is stable throughout. Eaton and Miranda (2013) stated that a more complex score is likely to cause issues for the musician, which will result in inaccuracies. While this BCMI provides a way for two people to co-operate in a musical setting, the outcome is a performance of a real-time composition. In respect to the criteria, the opportunity for composition spans as far as selecting pre-composed bars of melody with not a lot of musical input from the user. Essentially, this would only allow the participant to create sequences that then form a composition, something which can be achieved without this technology.

2.1.4. Discussion

For this discussion a graph has been presented (Figure 2.1) that represents where each approach has scored regarding the criteria. The first criteria explored which approach would offer suitable opportunities of harnessing EEG technology for a musical composition. This examines how the EEG data can be best utilised for creative purposes. As we can see from the graph in Figure 2.1, sonification scored the lowest. Both BCMI systems that were surveyed did not provide suitable opportunities of harnessing EEG technology for a musical composition. While Hinterberger and Baier's (2004) system has shown us that musical parameters can be mapped to data, this only offers the user very limited control over the musical outcome. Similarly to this, Baier et al. (2007) system focused on generating sound samples from epileptic disorders, which did not allow for the user to have any control over the musical outcome.

The second criteria explored which approach would allow for creative mapping techniques to be implemented in a BCMI that is to be used an an interactive compositional tool. Much like the first criteria, sonification scored the lowest in comparison to BCI control and musification. Baier et al. (2007) system only incorporated the note length, volume, and pitch, all of which were not controllable by the user. This would not be suitable for a BCMI developed as an interactive compositional tool as the user would not be able to interact with the composition. Hinterberger and Baier's (2004) system included note pitch and velocity which the user could potentially control through steering their EEG by focusing on particular instruments playing. However, the complexity of the technology used for this approach is far greater than the knowledge a composer would have. While there is no doubt that sonification can be used to form musical compositions, it would not be suitable for use as an interactive compositional tool.

In comparison to the sonification approach, musification provides suitable opportunities of harnessing EEG technology for a musical composition. Miranda and Soucaret's (2008) system had shown us that the user could control their frequency bands to prompt specific notes to form a composition. This would provide the user the opportunity to compose music that is representative of their biological state. Additionally, Miranda's (2010) explored the use of extracting musical elements from famous composers to form musical phrases, with these phrases being chosen depending on what frequency wave was most active. Although the user is not wholly controlling the composition, they have the ability to interact with it and thus have influence over the outcome. In regard to the first criteria, musification certainly provides suitable opportunities of harnessing EEG technology for a musical composition. Furthermore, both systems have included creative mapping techniques that would be suitable for a BCMI used as an interactive compositional tool.

Lastly, BCI control also offers the ability to compose music whilst also following musical rules. Miranda et al. (2011) and Eaton and Miranda's (2013) BCMI systems both utilised BCI control to successfully allow a user to make musical decisions. Miranda et al. (2011) BCMI allowed for a user to select a set of notes, and then choose a note from the given set by focusing their gaze on the corresponding icon, allowing the user to compose music note-by-note. Additionally, Eaton and Miranda's (2013) BCMI allowed for users to form a structure through the selection of musical phrases that were pre-composed. While this allows for the formation of a structure, it does not allow the user to control musical parameters such as the dynamics. In respect to the first criteria, the BCI approach does offer suitable opportunities of harnessing EEG technology for a musical composition, however, the opportunities it provides may not be suitable for a BCMI used as an interactive compositional tool. Firstly, these systems do not offer anything new to the compositional process, as it can all be achieved without this technology. This is certainly suitable for those with physical disabilities who cannot compose music the traditional way, but not for a composer looking for a new compositional tool. Lastly, the technology used alongside the EEG requires high-level programming knowledge and a greater understanding of signal processing mathematics; something which composers would not have skills in.

Regarding the research questions, musification appears to be the most viable approach for use within a BCMI system. In comparison to BCI control, musification presents less technical challenges that would occur during the development process. With BCI control, there are far more challenges that would need to be addressed, all varying and dependent on the technique used with it. For a composer using a BCMI as an interactive compositional tool, these challenges would be far beyond their skill set. In addition to this, musification offers more creative opportunities that will enhance the compositional process. Not only can this approach allow one to map EEG data to musical parameters, but the user can create meaningful changes to a musical composition that depicts their current biological state. This can still follow a set of musical rules that the EEG data is applied to, allowing the user to have some level of control.

Overall, it is clear that the musification approach would be best applied to a BCMI that is to be used as an interactive compositional tool. Musification allows for users to interact with compositions, provide sets of musical rules, and create music that is representative of their biological state.

Chapter Three: The System Development

Overview

This chapter introduces the developed system for this thesis with a clear introduction of the aims of the system. It draws upon the methods and approaches previously discussed in this thesis to develop a BCMI system as an interactive compositional tool. In addition, the musical aspects of this system are explored throughout the chapter with a clear rationale as to why they have been used.

3.1. Introduction and aim of the system

The previous chapters have discussed and evaluated many important aspects that will be used towards the development of this BCMI system. Firstly, it was determined that the alpha and beta waves were to be used for this system, this is due to the frequency bands being easy to detect in the frontal region of the brain, as well as being successfully used for musical control in other BCMI systems. Secondly, the results from the survey findings in Chapter Two concluded that musification would be the most appropriate approach to harnessing EEG signals. This approach ensures the musicality of the end result, as well as providing an adequate musical representation of the user's EEG data. This chapter implements these findings into the development of a BCMI system.

The aim of this BCMI system is to address both research questions and develop a BCMI system that can be used as an interactive tool for composers. To achieve this, the system will incorporate a pre-composed composition where the user will be able to control musical parameters via their brainwaves. As the focus of the system was to create an interactive compositional tool, it was deemed appropriate that a pre-composed composition was the foundation of the system. The user can then interact with this composition by changing musical parameters that are controlled via their alpha and beta waves.

3.1.1. Technical aspects of the system

The equipment used for this system was the g.tec g.Sahara active dry EEG electrode system. This system is made up of four parts, which are the g.GAMMAcap, g.SAHARA electrodes, g.SAHARAbox and the g.MOBilab+ (Figure 3.1)

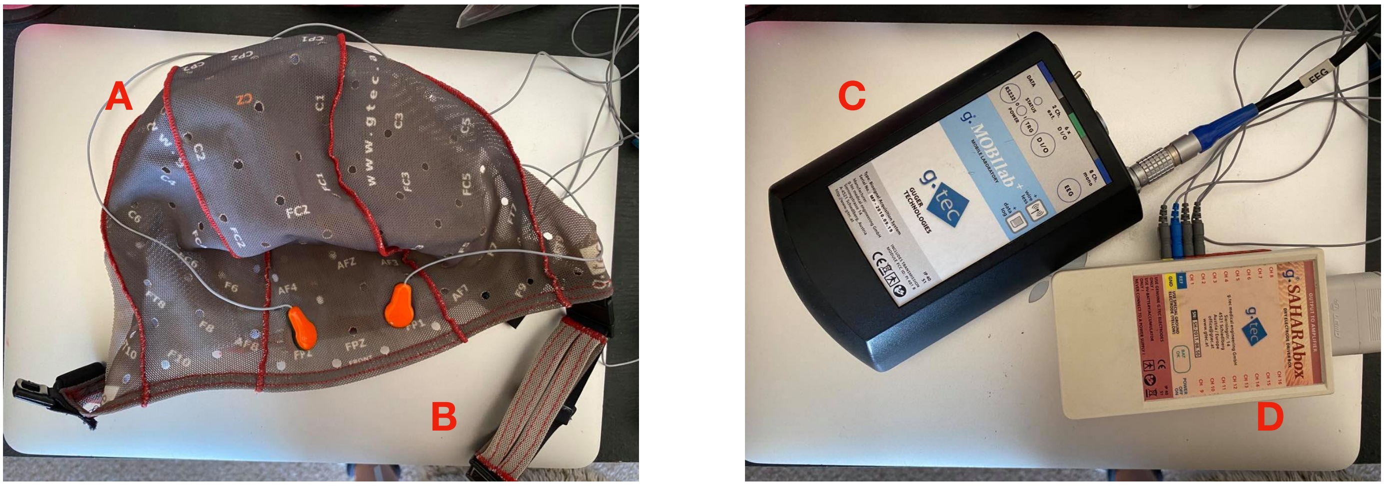

Figure 3.1: Components of the g.tec g.Sahara active dry EEG electrode system. (a) g.GAMMAcap, (b) g.Sahara electrodes, (c) g.MOBilab, (d) g.SAHARA box.

The g.GAMMAcap is a cloth cap which allows for the g.SAHARA electrodes to be positioned at the locations labeled on the cap. The g.SAHARA dry electrodes have a gold-alloy coating around eight pins that are designed to filter through to the hair, allowing for greater connection with the scalp. In comparison to wet electrodes where saline solution is applied to the electrode, these are easy to apply and does not require the need to wash hair or cap after use (Guger et al. 2012). The g.SAHARAbox powers the electrodes and acts as an interface for them, and the g.MOBilab+ is an analogue-to-digital convertor sampling at a fixed rate of 256 Hz for the EEG measurement. As the alpha and beta waves will be harnessed from the brain signal, it is appropriate to determine a location that is best suited for both frequency waves. Hinterberger and Baier

(2004) state that the parietal and occipital region of the brain can give higher amplitudes in the alpha range. Whilst this is true, Le Groux and Vershure (2009) argue against using the occipital region due to the user's hair causing too much interference with the EEG signals. Le Groux and Vershure (2009) also state that, since the amplitude is lower in comparison to the parietal and occipital region, the frontal region can prove successful in measuring the alpha waves. For the use of musical control, a higher amplitude is not necessary if one can get successful results from a lower amplitude. In addition to this, numerous BCMI systems that have utilised the alpha waves have recorded them from the frontal region of the brain with success (Lucier, 1964; Eaton, 2016). Furthermore, the beta waves are also commonly found within the frontal region of the brain and thus will allow for the recording of the two frequency bands simultaneously (Empson, 1986; Kropotov, 2009). This has been demonstrated in Eaton's (2016) BCMI, where the alpha and beta waves were being recorded from the same electrode position.

The electrodes will be positioned according to the international 10-20 electrode placement system; the standard placement system that the majority of BCMIs follow (Miranda and Brouse, 2005). As Straebel and Thoben (2014) stated, the smallest possible number of electrodes that are required is three; with all of them placed on the forehead, there will be one on either hemisphere of the brain, along with a ground electrode in the centre. Miranda et al. (2011) BCMI system used just three electrodes, as did Lucier's (1964) *Music for Solo Performer.* These placement of electrodes are located on the forehead of the user, with exception to the ground electrode, meaning that there will be less chance of interference from the user's hair and will provide a more reliable signal (Hundia, 2015). Taking this into account, the positioning of the electrodes for this system

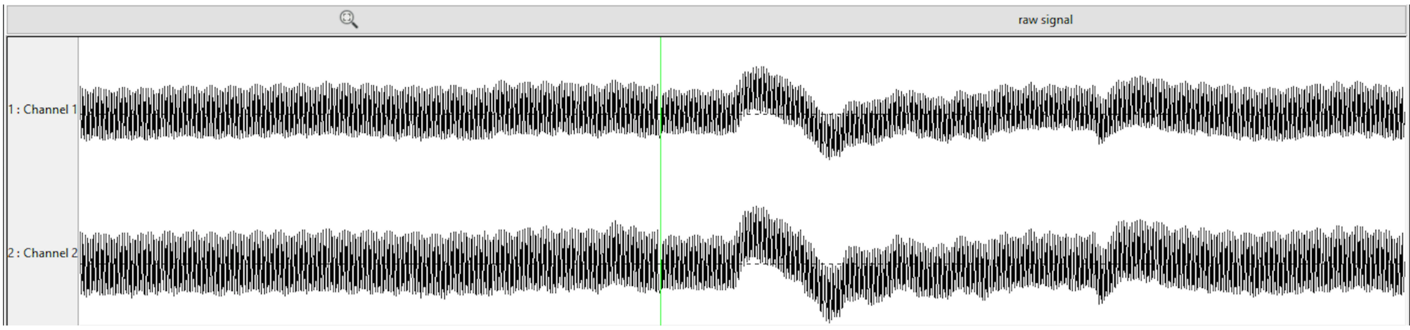

Figure 3.2: Screenshot of 20 seconds of the raw EEG signals before any filtering. Channel 1 is the electrode at Fp1 and channel 2 is the electrode at Fp2.

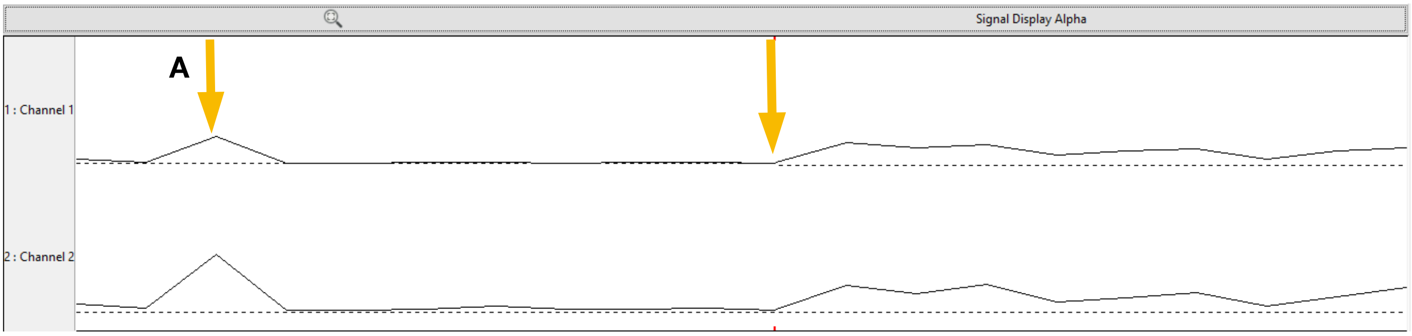

Figure 3.3: Screenshot of the filtered alpha wave; demonstrating the fluctuation of the eyes opening and then closing. The first half is eyes opened, the peak (A) is blinking artefact. The second half (B) is eyes closed. This fluctuation will be controlling note velocity of a composition.

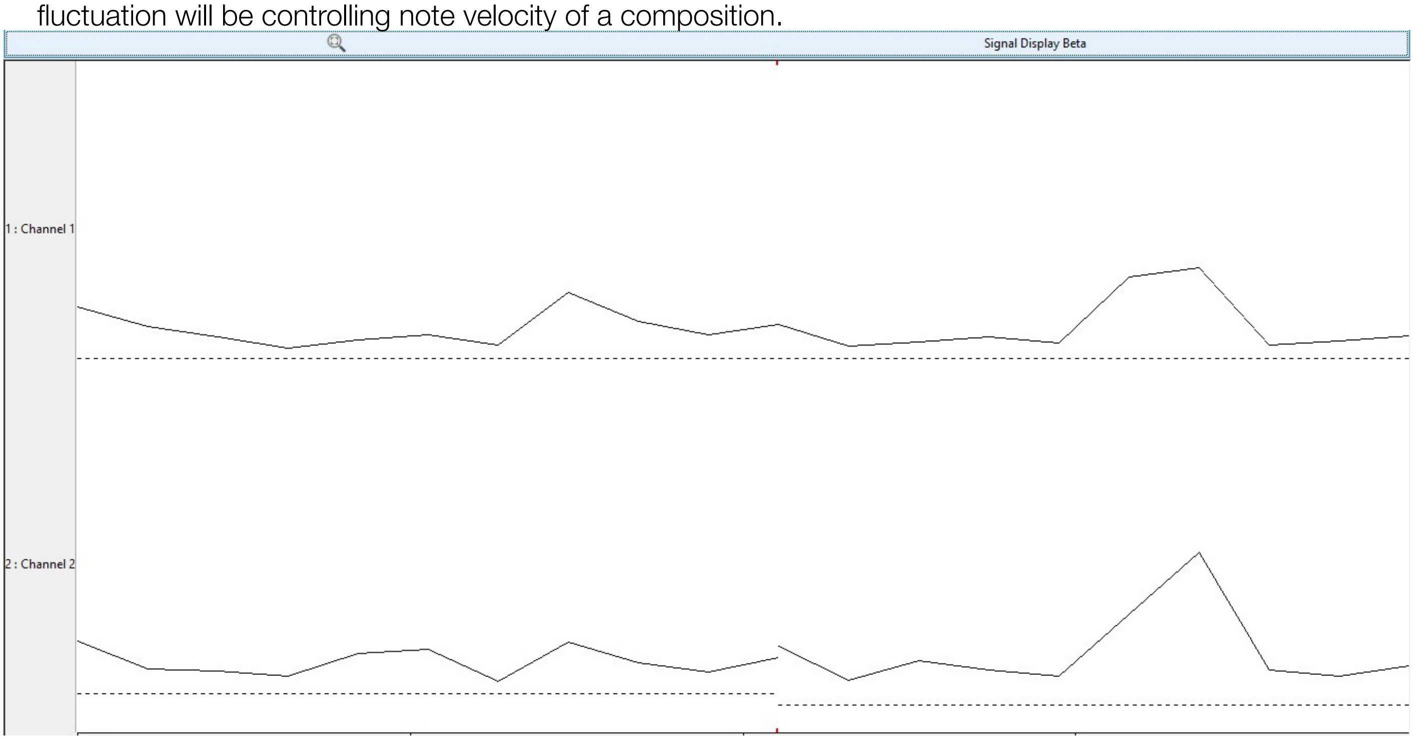

Figure 3.4: Screenshot of 20 seconds of beta wave activity.

will be located at Fp1, Fp2, a ground reference at OZ, and a reference electrode which is clipped onto the user's earlobe.

The raw EEG signals (Figure 3.2) are received via Bluetooth from the g.MOBilab+ at a sampling rate of 256 Hz. These raw EEG signals are sent to OpenVibe, a platform which provides a convenient interface between the EEG headset and the programming software. OpenVibe can be used to filter and process brain signals in real time, which allows for the extraction of the alpha and beta frequencies from the raw EEG signal, achieved using a band-pass filter. While there is much controversy to the exact frequency band of both the alpha and beta wave, the majority of literature in this field uses 8 Hz to 13 Hz for the alpha wave and 14 Hz to 30 Hz for the beta wave (Leslie and Mullen, 2011; Ramirez and Vamvakousis, 2012; Daly et al., 2014; Levicán et al., 2017). Therefore, to extract the alpha wave frequency from the raw EEG signal, a low cut-off frequency was set to 8 Hz and a high cut-off frequency was set to 13 Hz. For the beta wave, the low cut-off frequency was 14 Hz and the high cut-off frequency was 30 Hz.

During the first development, the fluctuation of the alpha wave will be responsible for controlling note velocity of the composition (Figure 3.3). In the first half of Figure 3.3, the user had their eyes open and was engaging their mind on a mental task. Here, the alpha wave is almost absent, with a peak in the wave at point A when they blinked. At point B is when they closed their eyes and relaxed. We can instantly see the fluctuation of the alpha wave as it becomes more prominent and active when the eyes are closed. This will be incorporated into the system so that when the user closes their eyes and the alpha wave becomes more active, the velocity will decrease and become softer so it resembles the relaxed state. Figure 3.4 shows the users beta wave whilst their eyes are open and they are engaging their mind on a mental task. Initially, the beta wave will be used to control chord selection.

To extract a specific time window from the continuous EEG signal, a time-based epoch object in OpenVibe was used. A time-based epoch is best described as signal ‘slices’ in which the length is configureable. Initially, a 500 millisecond time window was extracted. Ultimately, this meant that the musical parameters, such as the fluctuation of the note velocity, was changing every 500 milliseconds. This caused erratic velocity changes that decreased the quality of the composition. To overcome this issue, a 1000 millisecond time-based epoch was used, which instantly provided appropriate velocity changes that increased the outcome of the composition.

The data was then sent across to the visual programming software Max/MSP via Open Sound Control (OSC). OSC is a protocol for communication over networks that allow data to be sent from the EEG data acquisition software to Max/MSP. Max/MSP is the musical engine for the system and has been used in successful BCMI systems, such as Wu et al., (2010) system where it was used to construct a melody from EEG data and thus create a MIDI file. Wu et al. (2010) system included musical aspects such as harmony, structure, rhythm, and pitch, which all varied depending on the user’s arousal levels. Leslie and Mullen’s (2011) system, *Mood Mixer,* also employed this software to mix music according to the user’s mental states. Both of these systems provided accurate results. In addition to this, Max/MSP does not adopt text-based programming like Python or C++, making it appropriate for musicians who would not be familiar with high level programming languages. It is due to these reasons that Max/MSP was chosen as the musical engine for this system. Once the incoming EEG data was sent to Max/MSP, it was used to control a number of musical parameters that will be specified in the following system developments.

3.2. The first development

The first development of the system began by focusing on gaining successful control over the fluctuation of the alpha wave. For this initial development a short 16-bar composition was pre-composed (appendix A). This short composition forms part of the final composition which will be discussed further on in this chapter. The composition will playback in real-time on two instruments, a flute and electric guitar, and the incoming EEG data will alter the velocity of each note as it is played. The velocity represents how forcefully a key is pressed (e.g. a note on a piano that is struck softly will produce a softer sound). In terms of RQ2, this mapping technique will allow for the user to aurally understand the changes that their alpha wave is making. When the user is in a relaxed state with their eyes closed, the velocity of the flute melody will increase, and when the user opens their eyes and engages their mind on a mental activity, then the velocity of the flute melody will decrease and the electric guitar melody will increase. These instruments were chosen with the aim to represent the user's current biological state; the soft tone of the flute representing relaxation and the distorted tone of the electric guitar representing an active mind.

The MIDI velocity data ranges from 0 - 127, with 0 being the softest and 127 being the hardest. During the initial testing of this development, the velocity was extremely soft with no recognisable change throughout the playback. Due to this, the incoming data from the EEG signals were observed and it was noticed that the alpha wave signal was ranging from 0 - 0.19, causing the velocity to be extremely soft. To overcome this, it was required to change the scaling parameters in the Max/MSP patch so 0 would be assigned to the lowest velocity (0) and 0.19 would be assigned to the highest velocity (127). In addition to this, it was observed that the changes in velocity were not smooth, and were jumping from one point to another. This did not sound pleasant or suit the intended musical style, and was not aiding towards the relaxation to evoke the alpha wave. Due to this, mapping techniques were adopted to support the musicality of the velocity through adding additional objects to the Max/MSP patch, and thus addressing RQ2. These objects created a line; this meant that when the data goes from one point to another, it will automatically create a ramp from each data point so it plays back smoothly. For example, if the velocity went from 50 to 70, it would gradually increase as oppose to jumping from one point to the other. This achieved the desired result of the velocity gradually increasing or decreasing, which has allowed for an understanding into how the alpha wave can be used to control musical velocity. The next stage of this development focuses on developing a more sophisticated composition for the system and includes the use of the beta waves for controlling additional parameters.

3.2.1. The Composition

To develop the composition further, inspiration was taken from Eugene Bozza's *Aria,* composed in 1936 (Bozza, 1936). A pastiche of this piece was written, with the slow tempo and relaxed rhythms being the main extraction. In addition to this, inspiration was also taken from music of the Baroque era, in terms of instrumentation and structure. Laird (2004) stated that music of the Baroque era was intended to elicit various emotions, with certain parameters being used for their emotional impact. This suggests that utilising specific musical elements can represent the brainwaves being elicited. Due to this, certain parameters were chosen with the intention to not only represent these various emotions or mood states, but to also evoke them.

To begin the development of the composition, the rhythm was the first focus; it is known to be the starting point of a composition, because it defines the time signature for the piece (Jee et al., 2007). Rhythm is a time-based acoustical language that organises musical events into logical, comprehensible patterns, and can be used to communicate a sense of urgency and importance in a piece (Thaut, 2005; Douek, 2013). Simple and compound time signatures such as 4/4 (four crotchet beats per bar) and 6/8 (six quaver beats per bar) are the most commonly used time signatures as they provide a regular pulse to the music, which is a critical component to a composition (Thaut, 2005; Douek, 2013). In contrast, irregular time signatures such as 7/4 (seven crotchet beats per bar) or 5/8 (five quaver beats per bar) provide an irregular pulse throughout the music and create an uneasy feel (Jee et al., 2007). For this composition a steady pulse is used, as irregular time signatures may cause the user to feel uneasy and unable to relax, therefore unable to evoke their alpha wave. Musical elements such as duplets or triplets can be used to give an irregular rhythm to a regular pulse which can create variation to the composition. These are used in the composition and described further on in this chapter.

In terms of the tempo of the composition, a slow tempo was chosen for numerous reasons. Firstly, it was stated by Liu et al., (2018) that a fast tempo has been shown to decrease the alpha wave and increase the beta wave. This could be because the fast tempo results in the user being unable to relax, thus resulting in unintended velocity changes. As the alpha wave is responsible for controlling the velocity of the composition, the velocity would remain very low throughout the playback and there would not be much change. In addition to this, a slow tempo represents tenderness and relaxation (Jee et al., 2007). In consideration of RQ2, this compositional strategy may also help the user maintain a relaxed state for bringing forth their alpha waves.

Although musical tempo could have been used as a parameter for the user to control, the sudden changes to the tempo may have detracted from other musical parameters and therefore was not used as a control parameter. For example, if the tempo increased drastically then the user may not be able to hear significant changes from the velocity. While the tempo could be mapped to stay within a specific boundary, having too many parameters for the user to control may cause frustration or confusion.

Due to the above reasons, a tempo of 40bpm, also known as *Largo* (slow) was used. The style of this composition is inspired by the Baroque era, and therefore it is appropriate to describe the tempo using an Italian word. While in popular music, English terms such as “slow blues” or “fast rock” are often used to describe tempo, it is conventional in this style to describe the speed and expression of the music in Italian. This is because Italian was the language for the majority of composers during the 17th and 18th centuries. In addition to this, while tempo markings indicate the speed of the piece, they can also indicate the mood and expression. For example, *allegro* and *presto* both indicate a fast speed. However, *allegro* expresses a sense of joy at a fast pace whereas *presto* simply indicates speed. *Largo* indicates a slow tempo in a dignified style, whereas *lento* simply means to play slow. Tempo markings can also be followed by an additional Italian word that will tell the musician to play with a particular mood. For example, a*dagio con affeto* tells the musician to play slowly (*adagio)* with tender emotion (*con affeto)*. For this composition the tempo of the composition was described as l*argo con affeto* (slowly, in a dignified style with tender emotion). This was deemed appropriate as the alpha waves represent tender, relaxed emotions.

The structure of this composition followed the ternary form (A-B-A) whilst also taking inspiration from the ‘da capo aria’ structure, commonly used in the Baroque era. The ‘da capo aria’ structure is very similar to ternary form, however the repeated A section is filled with more embellishments (Bukofzer, 1947). This structure has been chosen to help elicit changes in the user’s alpha wave throughout playback of the composition. The A section is aimed at maintaining the user’s alpha wave and sustaining a low velocity, while the B section will feature contrasting rhythms that will aim to elicit spikes in the alpha wave fluctuation and thus increase velocity.

During the Baroque era, the ternary form would often be found in operas, concertos, and sonatas, being used solely for voice and accompaniment (Bukofzer, 1947). This composition has followed this structure and has been composed for one instrument and an accompaniment. In terms of RQ2, the use of one instrument will limit the number of control parameters and thus help maintain the user’s concentration, as too many parameters may cause distractions for the user and result in lack of control. In comparison to composing music the traditional way, this does limit the number of instruments that one can compose for. However, it is essential to maintain simplicity for the user who may be unfamiliar with this technology. Therefore, further investigation for the use of multiple instrumentation can be explored in future developments of the system. It was chosen to compose this composition for the flute as opposed to voice, as Schubert and Wolfe (2016) stated that the flute can represent a human voice in terms of the tonality and pitch, with its ability to play three octaves. As stated by Jee et al. (2007), the pitch, which is the frequency of the sound, can represent mood and emotion. For example, a high pitch can represent happiness and surprise, whereas a low pitch can represent sadness and solemnity (Jee et al., 2007). Due to this, the composition is composed with the aim to trigger fluctuations in the alpha wave through utilising a high and low pitch. This will be explained in more depth in chapter 3.2.2.

3.2.2. Sections

The first A section relies upon a rhythmic motif which forms part of the melodic design (Figure 3.5). This motif appears in the first two bars and is repeated throughout at a variety of pitches. The aim of these repeated phrases is so the listener becomes familiar with them and does not get distracted by too many rhythmic changes. As the phrases vary in pitch, they will elicit a fluctuation in the user's alpha wave. The higher the pitch of the phrase, the harder the velocity of the notes. This compositional strategy will allow for passive changes in the user's alpha wave. In addition to this, the motif helps maintain the structure throughout the composition, bringing recognition to the second A section when it is repeated. While the motif changes slightly in rhythm throughout the piece (often with added triplets or demisemiquavers), the dotted crotchet tied to the next bar remains the same.

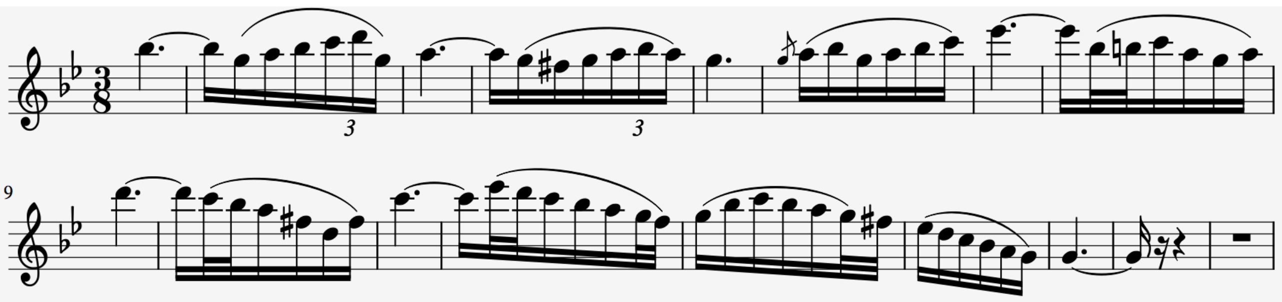

Figure 3.5: Extract from the composition, showing bars 1 to 17 and demonstrating the use of a rhythmic motif.

Bar 18 onwards (Figure 3.6) sees a change in the rhythm, with a motif of three semi-quaver triplets in quick succession. These triplets have been used in this composition to give a feel that the the tempo speeding up, with the aim to evoke a change in the alpha wave and therefore a rise in the velocity. The two bars of rests allow for the accompanying chords to become prominent.

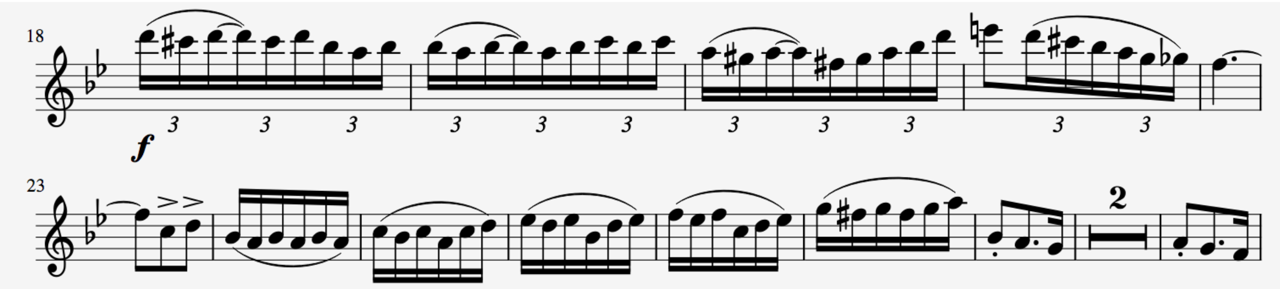

Figure 3.6: Excerpt from the composition, showcasing the change in rhythm through the use of triplets.

Section A is also distinguishable through the use of slurs. A slur is a musical articulation, meaning *legato* (smoothly; i.e to be played without separation). Articulation can vary in what it represents depending on the tempo, key, pitch or note length. A slow, legato composition forming mostly of crotchets and quavers could represent relaxation or sadness. However, a fast, legato composition could represent a sense of urgency or excitement. The slurs, along with the slow tempo, have been used in this composition to create a relaxing feel that will help the user maintain a calm and relaxed state.

Bars 38 - 39 (Figure 3.7) feature changes that is intended to cause fluctuation to the alpha wave and increase the velocity. These bars incorporate an accented quaver triplet and quaver duplet with the intention to cause an irregular pulse. As the user is in a relaxed state from the regular pulse, the sudden change to an irregular pulse is intended to cause fluctuations to the alpha wave and subsequently increase the velocity.

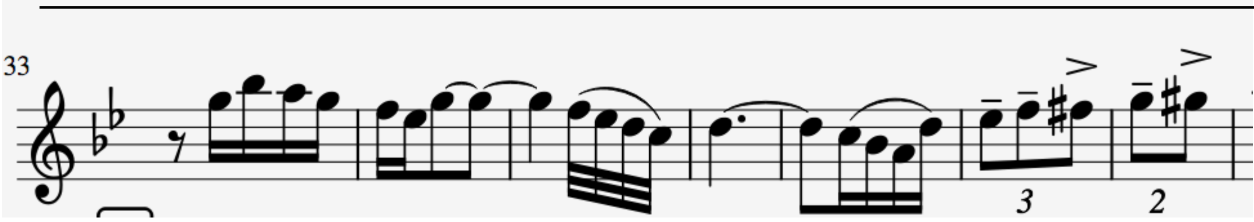

Figure 3.7: Excerpt from the composition; the lead up to section B, characterised by a triplet and duplet to cause a change in rhythm.

In a ‘da capo aria’ structure, the B section is either composed in the relative minor or dominant key to provide a contrast against the first section (Juslin and Sloboda, 2011). For this composition, the B section was composed in the dominant key, F major. This was chosen as oppose to the relative minor, as the relative minor would have created dissonance against the chords, which may trigger unwanted changes in the user’s brainwaves. This also aids the musicality of the composition.

The final A section is a repeat of the first A section, but with added musical ornamentation and rhythmic decoration. The beginning of the final A section begins with the familiar motif from the start of the composition, with the aim to evoke the user’s relaxed state and subsequently their alpha waves. This will cause a decrease in the velocity, providing contrast to the B section. The motif continues throughout with slight melodic changes, until the piece is concluded at bar 95. The composition finishes on the dominant note (F), the leading note (A), and then resolving to the tonic of the Bb major scale (Bb). This perfect cadence is used to maintain the user’s alpha wave at the end.

A total of sixteen chords were used in the system to not only enhance the musicality of the composition, but to also allow for additional creative mapping techniques to be implemented. These chords were inputted into a list on the Max/MSP patch using their MIDI value. The chords consisted of the tonic (I), dominant (V) and leading note (VII) chords of the Bb major scale. Root position, first inversion and second inversions of these chords were also used. These chords were chosen because the tonic and dominant chords are major and represent happiness which can aid in helping the user maintain a relaxed state and thus sustain their alpha wave. In contrast, the leading note chord is diminished which creates a tense sound which may create fluctuations in the user's alpha waves.

Initially, these chords were prompted to play when a particular MIDI value was present in the melody, such as 70 (Bb4) or 74 (D5). However, the MIDI values were in the melody at random intervals, meaning that there was no structure to the chords. This did not suit the musical style or structure of the composition. In addition to this, the random placement of the chords could cause unwanted changes in the user's alpha and beta waves which may disrupt the biological state that the user is trying to achieve. Due to this, the decision was made to have the chords prompted to play on the first beat of every bar, which instantly improved the musicality.

Originally, the velocity of the chords were being controlled by the user's beta wave. However, this caused the chords to play back quite loud and somewhat overwhelming as the user's beta wave was almost always present. As the chords serve as an accompaniment to the melody, they should be the same or lower in velocity. To overcome this, it was decided that the alpha wave will control the velocity of both the chords and melody. In addition to that, the scaling of the incoming data to the velocity of the chords was scaled so it does not reach 127 (the highest MIDI velocity value). This will make sure that the velocity of the chords is less than the velocity of the melody.

The next step was to improve the way the chords would play, so that some would play harmoniously and some would play melodically. This would improve the musicality of the composition. To do this, a chord template list was implemented in the Max/MSP patch. This list defined how many milliseconds there are between each of the notes in the chord and was created simply by inputting millisecond values into a list. A total of six templates were used, which provided enough variation for the composition. To select one of the six chords, the incoming EEG data from the beta wave is mapped from 0-6, with the lowest number mapped to the higher signal value. The chords are designed to be played on a piano and act as an accompaniment to the melody.

With two electrodes being used, and two channels per electrode, there were four channels in total. Both channels give the same data as it is a summation of electrode Fp1 and Fp2 along with the reference electrode. The separation of the channels make it easier to differentiate parameters in the Max/MSP patch. The alpha wave was used for controlling the velocity of the melody and chords, whereas the beta wave was responsible for controlling the chords and chord template.

3.2.3. System testing and discussion

The setup of the system took approximately 15 - 17 minutes. To begin the setup, the brain cap was placed on the user with the placement of electrodes at Fp1, Fp2 and OZ. Once situated on the user, the next step was to connect the headset to OpenVibe and gain decent quality contact between the electrodes and the scalp. At first, the raw EEG signal was filled with noise and interference. To eliminate this noise, the user placed the g.tec MOBilab+ box and the g.tec SAHARA box on their lap with their hands placed on top of it. This created a ground loop which reduced the amount of noise, instantly improving the signal quality (Eaton, 2016). The user was also required to sit still throughout the entirety of this test, as any movement could cause interference or inaccurate results (Rowen and Tolunsky, 2003). Once an adequate signal was acquired, the incoming data into the Max/MSP patch was observed and then scaled to fit the musical parameters.

The user sat with their eyes closed in a relaxed state to begin the test. The melody of the composition began to play quietly, which was to be expected when the user has their eyes closed. The user's alpha wave would also fluctuate when there was a rise in pitch in the melodic line and when the semi-quaver triplets were introduced in bar 18. While it was easy to determine that the user's alpha wave was controlling the velocity of the composition, it was extremely difficult to determine the changes that the user's beta wave was creating. Despite the chords occasionally being absent when the beta wave was absent, this did not provide a noticeable distinction as to when the beta wave was active or not. To improve this, there needs to be a clear indication of the beta wave so the user can try and manipulate it, such as an added harmony. As the original composition (melody and accompaniment) was composed with the aria structure in mind, including a harmony would no longer make it an aria structure as harmonies are not often used (Bukofzer, 1947). However, the composition would still be in ternary form. This was not viewed as an issue, only a change in the direction of the composition.

3.3. The final development

As the first testing of the system uncovered some aspects for improvement, this final development works on these aspects to form the final system. Firstly, this development introduces a melodic harmony to the composition with the velocity of the harmony being controlled by the beta wave. The velocity will be mapped to only reach a maximum velocity of 90, to avoid any overpowering against the melody. This addition will allow for a clear distinction between the alpha and the beta wave. Secondly, this development introduces the ability to change the composition from major to minor (and vice versa). The alpha wave will be controlling the major key, and the beta wave will be controlling the minor key. Both parameters will provide an additional creative mapping technique to implement and will serve as another parameter that will be representative of the user's current mental state (as discussed in Chapter Two).

In the first A section, the harmony is formed of tied dotted crotchet notes a major third or major fifth down from the melody (Figure 3.8) which is an appropriate and common way to harmonise (Jee et al., 2007). This also means that the harmony will not cause any dissonance with the melody, which may cause unwanted fluctuations in the users alpha wave whilst they are trying to maintain a relaxed state.

Until the lead up to section B, the harmony is mostly formed of long notes to support the melodic line or playing in unison with the melody. In bar 33 until section B, the harmony is either playing in unison or an octave below the melody. However, section B uses a mixture of minor third and major second intervals as the section changes to the relative minor. These intervals aid with the aim that section B is composed for, which is to evoke fluctuation of the user's alpha wave and bring forth their beta waves. The final A section is very similar to the first A section in terms of the harmony, with the harmony either playing in unison or holding long notes to support the melody.

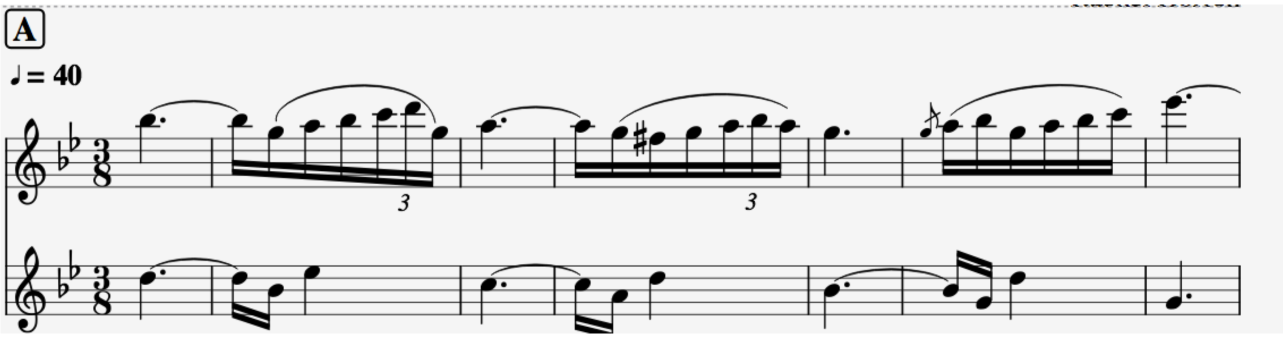

Figure 3.8: Excerpt from the composition; the first 7 bars of the piece with the added harmony part.

The next development of the system is to allow for the user's brainwaves to control in real time whether the composition plays back in a major or minor key. Jee et al. (2007) stated that the key of the music can play an important role in terms of changing the overall mood. The diatonic tones such as major or minor can also signify certain emotions; with a major key signifying happiness and a minor key signifying sadness (Jee et al., 2007). For this system, the major key will be represented by the user's alpha wave and the minor key will be represented by the user's beta wave. The change of key will be controlled depending on what is more prominent; the alpha or the beta wave. This will be changing throughout the playback of the composition.

As the composition is composed in the key of Bb major, apart from the B section which is in the dominant key - F major, it was decided that when the key changes to a minor key it will be in the parallel minor - Bb harmonic minor. This is so the chords that are chosen for the composition, despite being in a major key, will sound aesthetically pleasing compared to if the composition was in the relative minor - G minor. To allow for this in the Max/MSP patch, objects were used to select the third, sixth and seventh note of the Bb major scale as they were played from the MIDI file. These notes were then lowered by a semitone when the beta wave became prominent, thus changing the composition to the minor key.

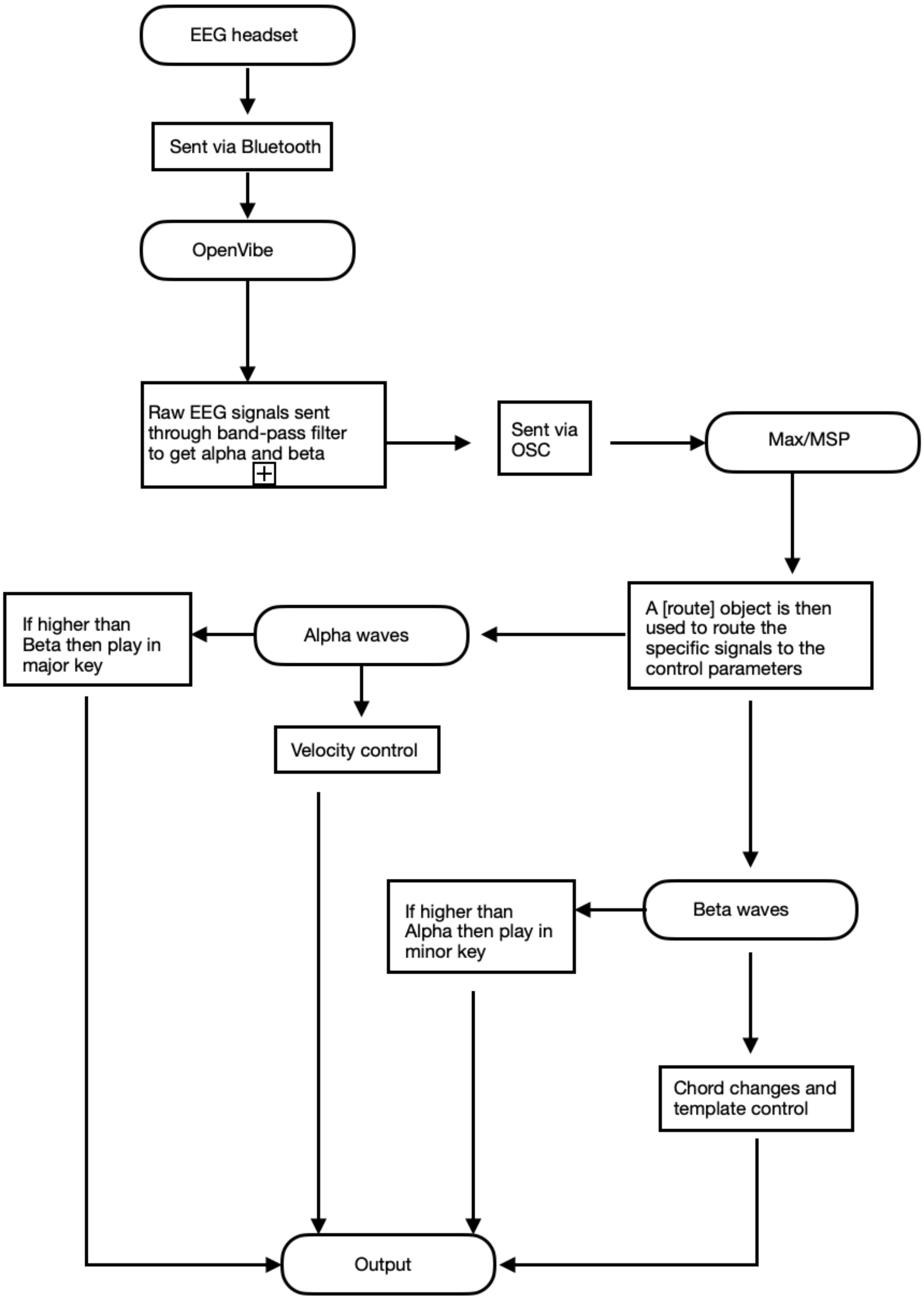

Figure 3.9: Flow diagram of the final set-up of the system.

The aim was to only have the harmony playing at a higher velocity when the user has their eyes open and their beta wave was prominent. However, as the harmony would be rising and lowering in velocity quite frequently, it was causing a distraction to the user. This made it harder for the user to maintain a relaxed state for their alpha waves. Due to this, it was decided to use the alpha wave to control the velocity of the entire composition; the harmony, melody, and chords. Therefore, the beta wave was responsible for controlling the chord selection, chord templates and the minor key.

3.3.1. System testing and discussion

To demonstrate the BCMI for the reader, a video of it being tested was recorded (see appendix B). As per the previous system development, the set-up remained exactly the same. A flowchart of the final setup of the system can be seen in Figure 3.9.

Prior to the start of the test, the user had pressed the play button on the Max/MSP patch to allow themselves time to relax, sit in a comfortable position, and allow the electrodes to obtain a decent quality contact. To begin with, the user had their eyes closed and was in a relaxed state to prompt their alpha waves. The user remained with their eyes closed for one playback of the composition. The composition began playing in the major key, although occasionally a minor note would play (timestamp 0:50). This means that the beta wave has briefly become more prominent than the alpha wave; shortly after this, the composition changed back to the major key. This can be looked upon from a compositional view as an accidental, where a note that is not part of the scale is played. The composition begins low in velocity which creates a soft tone, representing the users relaxed state of mind. Throughout the playback we frequently hear a rise in velocity when certain compositional changes occur, which is what was intended when they were composed. At 1:12 we hear the semi-quaver triplets from bar 18 (Figure 3.6) along with a fluctuation in velocity. At 2:05 and 2:15, the pitch rises, causing the user's alpha wave to fluctuate, and therefore increasing note velocity. Unfortunately, section B did not cause the user's alpha wave to fluctuate as planned. This could be due to the fact that it was a considerably shorter section in comparison to the A section, and therefore did not allow enough time for the user to recognise the compositional changes that had been made.

The first playback of the composition ends at 3:09 . The composition will repeat until the user presses the stop button on the Max/MSP patch. This can also be changed to loop a specific amount of times if required. During the second loop of the composition, the user began by opening their eyes and focusing their mind on a mental activity. This caused a key change from major to minor, with a rise in velocity at 3:12. Although the fluctuation of the alpha wave was causing many increases and decreases in note velocity, 3:40 demonstrates a rise in velocity in response to the triplet rhythm and increasing note pitch. Nonetheless, the velocity during section A remained low, despite changes to and from the minor key.

During the third and final loop of this composition (timestamp 5:38), the user opened and closed their eyes at random intervals, demonstrating the response time between the opening/closing of the eyes and the changes in the musical parameters. At 7:18, the user closed their eyes and instantly the composition returned to a major key with a lower velocity. At 7:28, the user opened their eyes, which brought the composition into a minor key with a slight raise in velocity. This continues until the end of the video.

It was observed throughout the testing that the user had adequate control over their alpha and beta waves, and subsequently the musical parameters. In addition to this, this system has demonstrated that the elements specifically included in the pre-composed composition to elicit fluctuations in the alpha wave was successful. As it was observed that the B section was lacking the parameters to cause these fluctuations, a new and improved composition was developed (appendix C). This B section was composed to create a noticeable contrast with the A section, to evoke fluctuation in the user's alpha wave. As the A section was composed to help the user maintain a relaxed state so their alpha wave would be prominent, the B section is composed to trigger a mentally engaging thought process which will reduce the alpha wave and increase the user's beta wave.

Aside from the change in key, this improved B section can also be identified through the use of staccato notes, seen in Figure 3.10, in contrast to the slurs being used in section A. A staccato note means the note will not ring out and will have a very quick decay. The 'da capo aria' structure is also known for its use of musical ornamentation and embellishments, especially in the second section (Bukofzer, 1947). In this section, the composition incorporates trills, which are rapid alternations between two adjacent notes. These trills are aimed to help maintain the reduction in the user's alpha wave amplitude, therefore increase velocity. The B section lasts for 18 bars, with bar 58 ending on the dominant note of the F major scale (C), creating an imperfect cadence.

Following this, the system was briefly re-tested and recorded to demonstrate the B section, which can be viewed in appendix D. Due to restrictions out of my control, this re-test was carried out under different conditions in comparison to the first test. This included increased background noise causing distraction to the user. Section B begins at 0:14 (appendix D), with the user's eyes closed. At 0:19, the user opens their eyes, which increases the velocity and causes fluctuations in the minor key (timestamp 0:36). At 0.49, a trill causes a key change, going from major to minor. This was what was the trill, alongside other articulation, was intended to cause. The repeated section A begins at 1:03 with the user closing their eyes, which causes a decrease in the velocity. A rise in pitch at 1:24 causes a brief increase in velocity and minor key fluctuation, which is what was intended by a rise in pitch.

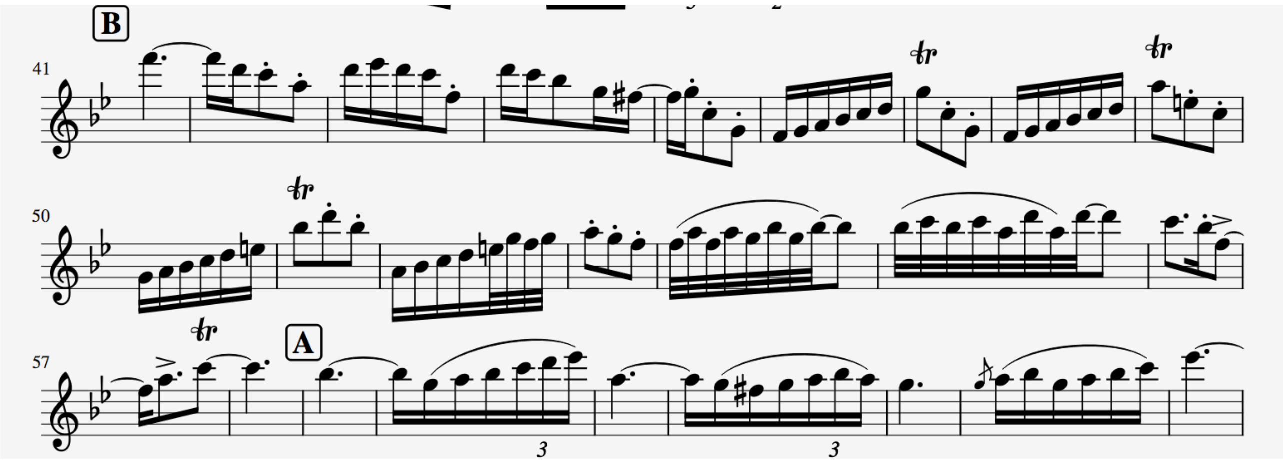

Figure 3.10: Excerpt from the composition; Section B.

These tests have shown that the user's alpha and beta waves have responded to the intended musical parameters that were composed with the intention to elicit brainwave fluctuations. In addition to this, it was also observed that it is easier to control the alpha and beta waves with less distraction, and therefore is recommended that future tests are conducted in quiet environments.

3.4. Overall discussion of the system

In terms of RQ1, this developed BCMI system allowed for numerous creative and technical opportunities to be implemented, but it also came with challenges. The use of a pre-composed composition allowed for specific musical elements to be included that would elicit changes in the two frequency bands that were used. This provided the user with the creative opportunity to have a level of control over note velocity, key changes, and chord changes, dependent on their current mental state. While this provided variety throughout the piece, it also provided interesting and meaningful musical results. Although the user can learn to control their brainwaves to some extent, there is still a large portion that is uncontrollable. This technical challenge was addressed in Chapter 1, with inaccuracies said to be caused by electrical interference or muscle movement.

During the testing of the system in Chapter 3.3.1, there were occasions where the user had attempted to relax to bring forth their alpha waves, but instead the beta wave became more prominent. While this certainly could be caused by electrical interference or muscle movement, it could also be due to the user requiring more practice with the system and therefore further work is required to determine this. Despite this, these unintended changes do not negatively affect the end result of the composition because of the specific structure and rules that the system follows. In addition to this, the development of the system in Chapter 3.3 uncovered some technical challenges regarding the beta wave. Initially, the beta wave was responsible for controlling the velocity of the harmony, as if to have the melody and harmony as two separate instruments. However, this had to be changed due to the fact that the harmony was either overpowering the melody, or completely absent. It was therefore decided to have the velocity of both the harmony and melody, as well as the chords, to be controlled solely by the user’s alpha wave.

In regard to creative challenges, there was a limit with the chords that could be used. As the key of the pre-composed composition is in Bb major, the chords chosen consisted of the tonic (I), dominant (V) and leading note (VII) of the scale. The tonic and dominant chord was chosen as they are major chords which can help the user maintain a relaxed state, whereas the leading note is a diminished chord which creates a tense sound and thus may cause fluctuations in the user's alpha waves. The use of only three chords limited the creativity in comparison to composing the traditional way; where any number of chords that are made up from the notes within the scale can be used. However, if all the chords of the Bb major scale was included then the minor chords would greatly change the mood of the music, which may cause the user the inability to relax. In addition to this, the chords chosen are also in the F major scale (B section), which avoids dissonance against the melody that may trigger unwanted changes in the user's brainwaves.

In terms of technical opportunities, this system allows for any pre-composed composition as a MIDI file to be implemented within the system, with the requirement of a few edits being made in the Max/MSP patch to match the compositions tempo, time signature, key, and chords. This allows the pre-composed composition to be of any genre, however, it is recommended that it contains compositional strategies that are aimed to elicit changes in the user's frequency bands. Additionally, it is recommended that the composition contains a maximum of three instruments that each have controllable parameters, to ensure that the relationship between the data and music is recognisable. Further research is recommended to explore the incorporation of additional instruments. The outcome of the composition cannot be scored or replicated. While this may be viewed as a creative challenge due to the fact the final composition cannot be replicated, it can also be viewed as a creative opportunity because the end result of the composition will change each time one uses the system. Although this composition is not scored, there can be some ‘rules’ put in place, much like Lucier’s *Music for Solo Performer.* A set of rules have been provided for this system explaining how to use the system (appendix E).

Taking into consideration RQ2, this system utilises mapping techniques that offer an interesting approach to interactive compositional strategies. Firstly, the mapping of the alpha wave to note velocity provided the user with an easy-to-understand auditory representation of their alpha waves. This enabled the user to understand how their brainwaves are interacting with the system, allowing them to attempt to adjust their mental state in order to change the parameters. Secondly, despite the difficulties regarding the beta wave in Chapter 3.3, mapping it to a minor key provided a clear auditory representation of the beta wave and allowed the user to understand the changes that were being made.

The composition is formed of multiple compositional strategies aimed to elicit changes in the user’s brainwaves. As demonstrated in Chapter 3.3.1, examples of these strategies included a rise in pitch which caused fluctuations in the user’s alpha waves and subsequently the velocity, whereas held notes and the familiar motif helped the user relax and thus lower the velocity. The majority of these strategies achieved the desired results, with the exception of section B of the composition. It was observed in Chapter 3.3.1 that, as this section was considerably shorter in length than the previous section, the user did not have enough time to recognise the compositional changes and thus change their mental state. This was reflected in the lack of velocity change or key change throughout this section. Due to this, it was essential to expand this section during the final testing in Chapter 3.3.1 to allow enough time for the user to respond to the parameters.

In addition to the above compositional strategies, Chapter 3.2.1 determined that a slow tempo would be most appropriate for the pre-composed composition. This is because a slow tempo represents relaxation which may help the user maintain a relaxed state for bringing forth their alpha waves, whereas a fast tempo may have the opposite effect. In addition to this, the slower tempo allowed for other compositional strategies, such as the duplet and triplet which only lasted for two bars, to be clearly heard. This enabled the user time to react to these compositional strategies as intended. In comparison to composing the traditional way, this limits the ability to compose energetic and upbeat compositions that represent excitement and happiness.

Chapter Four: Summary and Conclusions

Overview:

This chapter summarises the conclusions reached throughout this thesis and discusses these conclusions with the research questions and aims that were outlined in the introduction to the thesis.

Summary

This thesis has explored how brainwave control can be used to develop methods of integrating BCMI technology into the compositional process to create an interactive compositional tool. At the beginning of this study, previous BCMI research was reviewed in order to outline a framework for the system. The EEG, a method of recording brainwaves, was selected due to its suitability for musical applications. The musification approach to harnessing brainwaves was chosen because of its ability to provide a level of control over musical parameters, and for this control to be representative of the user's biological state. This approach ensured the musicality of the end result. Furthering discussion of this, the research aims and questions have been addressed as follows:

RQ1. What are the creative and technical challenges and opportunities of harnessing EEG technology in a musical composition?

Challenge 1: The use of multiple frequency bands.

Chapter 1.2 discussed the use of frequency bands in relation to music composition, and explored the potential of using multiple frequency bands. It was determined in this chapter that utilising all five frequency bands would not be suitable for musical applications due to the low accuracy rate of simultaneously recording them, and that some frequency bands (delta and theta) are only present during deep sleep or wakefulness. On the other hand, the use of multiple frequency bands allows for additional control parameters to be incorporated into the system, and therefore Chapter 1.2 concluded that utilising both the alpha and beta frequency bands for the purpose of music control will allow for an adequate variety of control parameters to be used. These frequency bands are relatively easy to understand and thus reduces any technical challenges that could occur. It is therefore recommended that the alpha and beta frequency bands are used for musical control.

Challenge 2: The compositional limitations.
One of the main compositional limitations of harnessing EEG technology for musical compositions is the lack of being able to compose note-by-note using this system whilst maintaining musicality and control from the user. As mentioned in the introduction, BCMI systems such as Pinegger et al. (2017) provided the user to compose note-by-note through the use of eye-gazing technology, but did not offer a composer any new compositional tools that would aid the process of the compositional development. Therefore, a pre-composed composition is recommended; allowing the user to control specific musical parameters.

In regard to a pre-composed composition, as mentioned in Chapter 3.4 it was challenging to compose a complex piece of music whilst also maintaining the relationship between the data and the music. To enable the user to understand what is going on in their brain and how their brainwaves are interacting with the system, the composition had to maintain some sort of simplicity. If there were tempo changes or complex harmony then this would have distracted the user and would not have been helpful for the user to determine how their brainwaves are interacting with the system. While it is currently recommended that a pre-composed composition maintains a level of simplicity, more research is required to determine specifically how these musical elements would affect the user.

Challenge 3: The velocity.

In Chapter 3.2, the alpha wave was responsible for controlling the velocity of the melody, with the beta wave controlling the velocity of the harmony. However, the development of the system throughout Chapter 3.3 concluded that the alpha wave would be responsible for controlling the velocity of both the melody and harmony, and the chords. Although the aim was to have the velocity of the harmony controlled by the beta wave as if two different instruments were playing, this was not feasible due to the absence of the beta wave when the user was relaxed.

Opportunity 1: A meaningful representation of the users biological state.

An opportunity of harnessing EEG technology in a musical composition is the ability to include a meaningful representation of the users current biological state. With the inclusion of the alpha and beta waves, the user is able to hear the musical changes that represented their relaxed and alert state. This provides a different method of composing music that would not be achievable using the traditional methods of composing.

Opportunity 2: A variety of outcomes from one pre-composed composition.

This system allows for a variety of outcomes from one pre-composed composition. The pre-composed composition essentially acts as a compositional space which allows the user to navigate around it using their alpha and beta waves. The parameters within this space that can be changed are pre-defined, allowing for the composition to maintain musicality and structure. The outcome of the composition will vary each time, and can be dependent on the user’s current biological state or whether or not they have a level of control over their alpha and beta waves. In comparison to composing the traditional way, this system allows for the user to interact with the composition.

Opportunity 3: An alternative method to composing music the traditional way.
One of the overarching opportunities for utilising EEG technology for musical compositions is that it provides an alternative method to composing music. This method adds the element of interaction to the process; allowing the user to navigate around their pre-composed composition and manipulate parameters to be representative of their biological state.

RQ2. What compositional strategies and mapping techniques can be adopted to integrate brainwaves into the compositional process?

Compositional Strategies:

To develop a system that is to be used as an interactive tool for compositional purposes, it was essential to contain elements that are not achievable without this technology such as the auditory representation of the user's current mental state. It was therefore concluded that the most suitable approach would be to use a pre-composed composition containing compositional strategies aimed to elicit the alpha and beta waves. The pre-composed composition used for this system included the following compositional strategies:

- Three sections

The pre-composed composition consisted of three sections (A-B-A), with each section aimed to elicit either the alpha wave, beta wave, or both. This allowed for each section to focus on one frequency band, by including specific parameters such as articulation or melodic changes aimed to elicit and maintain that frequency band. For example, the A section included slurs to provide a smooth melodic pattern and help maintain the relaxed state of the user, whereas the B section consisted of staccato notes and trills aimed to bring forth and maintain the user's beta wave. The first test in Chapter 3.3.1 demonstrated that the musical parameters specifically included in section A of the composition successfully evoked fluctuations in the user's alpha wave. However, it was also observed that the beta wave did not become prominent during the B section as planned. This was due to two reasons: a lack of musical parameters and a significantly shorter section in comparison to the A section. Upon this discovery, additions were made to expand the B section and include further articulation such as staccato notes and trills. A re-test was then conducted in Chapter 3.3.1 and the user successfully demonstrated the alpha wave in the A section, beta wave in the B section, and a combination of both in the final A section. This compositional strategy is recommended for future systems that aim to elicit multiple frequency bands in one composition.

- A familiar motif

The aim of using a familiar motif throughout the A sections of the composition was to help maintain the user's relaxed state and thus the alpha waves. Chapter 3.3.1 demonstrated that the user's alpha waves were mostly stable throughout the playback of this motif. When the user opens their eyes and focuses their mind on an engaging task, the motif is often played in the major key, meaning that the alpha waves were prominent. However, due to the fact that the user had previously not responded to the short B section, it is questionable as to whether the user would have had time to respond to the short two-bar motifs. Therefore, it is recommended that further investigation into response time between the music and the frequency bands is undertaken. Despite this, the motif was only used in the A sections, and therefore can also be used to signal what section the music is in.

- Rhythmic changes

Multiple rhythmic changes were made throughout the composition with the aim to elicit fluctuations in the users frequency bands. Chapter 3.2.1 explored the use of rhythmic changes that represented and evoked various emotions or mood states. This concluded that maintaining a steady pulse by using simple or compound time signatures such as 4/4 or 6/8 would help the user maintain a relaxed state, as irregular time signatures create an uneasy feel and therefore may cause the user to feel uneasy and unable to relax. Therefore, it is recommended that irregular time signatures are avoided unless the aim is to evoke uneasiness in the user. Nonetheless, Chapter 3.2.1 discussed that musical elements such as duplets or triplets can be included in a composition to give an irregular rhythm to a regular pulse. These musical elements were used in the lead up to section B and only consisted of two bars. Therefore further investigation is suggested to establish the effects that specific musical elements have on the users frequency bands. Nonetheless, this rhythmic change provided a clear indication that the B section was coming up.

Mapping Techniques:

To develop a system that is to be used as an interactive tool for composing music, certain mapping techniques were used to help maintain the musicality of the end result, and to ensure that there is a clear representation of the user's current biological state.

- The velocity

As mentioned in Chapter 3.2, the mapping of the alpha wave to note velocity provided the user with an easy-to-understand auditory representation of their alpha wave. More specifically, Chapter 3.2 explored certain mapping techniques that were adopted to support the musicality of the velocity and create a smooth transition as the velocity fluctuates. This smooth transition is essential in maintaining the users alpha wave, as the first development of the system in Chapter 3.2 stated that abrupt changes in velocity did not aid towards relaxation to evoke the alpha wave. In addition to this, Chapter 3.3 established that the velocity of the harmony was frequently overpowering the melody and fluctuating between high and low velocity quite quickly. This caused a distraction to the user which it harder for them to maintain a relaxed state for their alpha waves. Due to this, the velocity of the harmony was mapped to the user's alpha wave. To ensure that the harmony does not over power the main melodic line, it is recommended that the velocity of the harmony is mapped to a maximum of 90.

- Key changes

In addition to the pre-composed composition consisting of a major and minor key, the alpha and beta wave was also mapped to manipulate these keys. If the alpha wave was more prominent, then the composition would playback in the major key, however, if the beta wave became more prominent, then the composition would playback in the minor key. This allowed for a clear real-time auditory representation of both frequency bands and the users current biological state.

- Chord selection

The beta wave was mapped to the chord selection, which provided added musicality to the composition. It was difficult to tell how the beta wave was manipulating the chord changes due to there being a mixed selection of chords and templates. However, when the beta wave was absent then no chords would play, which happened occasionally.

To summarise the above, RQ1 concluded that there are both challenges and opportunities that arise from harnessing EEG technology in a musical composition. The challenges on the technological side were often minimal and any adjustments made to rectify these issues would not cause any significant problem, whereas the compositional challenges restricted the composers intentions for the pre-composed composition. In contrast to this, the opportunities that this technology can provide can outweigh the challenges. On the technological side, this technology provided a meaningful representation of the user's current biological state, providing the user with an alternative method of composing music. Additionally, in regard to the compositional opportunities, this technology allows for a user to interact with a pre-composed composition, thus creating a variety of outcomes. RQ2 concluded that there are numerous compositional strategies and mapping techniques that can be adopted to integrate brainwaves into the compositional process. The compositional strategies allowed for a structured change in the users alpha and beta waves, whilst the mapping techniques helped maintain the musicality of the end result, as well as providing a clear real-time auditory representation of both frequency bands.

In conclusion, this thesis has demonstrated a successful BCMI system that functions as an interactive compositional tool for musicians. It has recognised the knowledge of a musician and has outlined the methods and techniques which are recommended to be used when developing such system. To further understand the implications of this research, the following future work is recommended.

A summary of recommended future work:

- An investigation into how musical elements such as articulation and rhythm affect the user's brain waves. This will allow for an understanding of how specific musical elements can be used to trigger certain brainwave frequencies.
- An investigation into the response time between the music and the frequency bands. This will enable pre-composed compositions to contain elements lasting for the correct amount of time it takes to cause specific fluctuations in the frequency bands.
- An exploration of various genres of pre-composed compositions implemented in the system. This will provide research into the capability of the system being used for a variety of genres as oppose to just one.
- The system developed for this thesis included a limited amount of musical parameters and instruments. It is suggested that further research is undertaken to include additional parameters and/or instruments without affecting the simplicity of the system.
- Finally, further recommendations include research into this compositional tool being applied to therapeutic applications as well as creative applications such as in a performance setting. Following on from this development it is hoped that such technology can be utilised in the compositional process as common practice.

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Appendices

Appendix A: The first 16 bar composition used to trial the fluctuation of the alpha wave.

Appendix B: A video recording of the system being tested.

Appendix C: The score of the composition.

Appendix D: A video recording of the improved “Section B” being tested.

Appendix E: A list of compositional rules.

Appendix A

Composition for the testing fluctuation of the alpha wave

Rachel Horrell

Appendix C:

Music for the brain: *Rilassamento*

Rachel Horrell

2


74
Fl.
Fl.
f
78
85
92
tr

Appendix E:

Composition Rules

These rules have been designed to be used with the BCMI system developed for the thesis. This includes the equipment and the pre-composed composition.

1. Ensure that the correct MIDI files are loaded into the Max/MSP patch.
2. The EEG headset used with this system was a g.tec SAHARA dry electrodes system. The electrodes must be placed with the following EEG electrode placement: Fp1, Fp2, ground electrode at FpZ and the reference electrode clipped onto the ear. Allow time to gain good quality signal contact.
3. Press the play button on the Max/MSP patch.
4. Note velocity will change depending on your alpha wave. To create a lower velocity, close your eyes and relax. To increase the velocity, open your eyes and actively engage your mind.
5. Chord selections will be made from your beta waves.
6. The composition can changed from major to minor, and vice versa. To have the composition play in the major key, close your eyes and relax. To have the composition play in the minor key, open your eyes and actively engage your mind.