From Invisible to Visible

the EEG as a tool for music creation and control

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Foreword

This thesis is addressed to those with an interdisciplinary interest in the arts (particularly music) and the sciences (particularly neurosciences, psychology of perception, and the study of self-organizing systems). However, readers whose backgrounds are in other areas such as cognition, philosophy, computer science, or musical instrument design may find this thesis interesting as well. It is hoped that the ideas presented herein may contribute in some way toward increasing our breadth of understanding understanding the use of machine learning processes as a tool in the arts. Specifically how this tool can be used to help performers and composers to organize data and extract useful information from large and chaotic data structures, such as in the case of complex sensors.

Abstract

What is nowadays called *"brainwave music"* started in the late 60s and 70s with the translation of the electrical brain activity detected through the electroencephalogram (EEG) into sound. Brainwave music developed mainly in the United States with the pioneering experimentations by Alvin Lucier, Richard Teitelbaum and David Rosenboom. The aesthetics and technology used during their initial performances does not seem to have evolved since, despite the advent of digitalization and the possibility to easily implement statistical and analytical methods of signal processing, and the availability of faster computers with larger memory storage. The main objective is to dematerialize the performer's gesture through the brain signal, which is the fundamental element to reach telekinetic control, and let the performer control some aspects of the music performance. As a direct consequence though, the audience has nothing more to observe, the music produced is completely abstracted from any visible cause-effect relationship, leaving no cues for the audience to understand what is being control. From a deeper inspection of the literature, it appears evident how brain control is still an unreached holy grail. That is to say, some degree of control can be achieved but it is rarely reliable, precise, or qualifiable to drive the complexity of a music composition. The first chapters of this thesis show how the understanding of some of the brain features is a necessary requisite to reach a more systematic control, which can open more creative use of brain signals, and probably suggest alternative visual strategies to display new aspects of the brain to the audience. The last chapter of this thesis exposes a simple personal approach to solve the intrinsic technical and artistic limitations of present brainwave music applications. Using correlation on several instances of brain signals, I train the system to extract patterns connected to specific mind states of the performer and use pattern recognition algorithms to detect similar patterns during the live performance. These techniques allow conscious and rather reliable control of three variables of a system in a non synchronous way. The simplicity and limitations of such a system are discussed in the framework of artistic performances. The use of a dynamic mapping, that changes how the music parameters are connected to the few brain variables, can partly expand the expressive possibilities of such a system during a live performance. I expose the approach I used for my performance *"Fragmentation"*. The performance attempts to simultaneously control few parameters of a solo instrument and the timeline of the structure of the whole composition. Future research is needed to implement better methods for analysis of the EEG signals and mapping strategies.

Contents

1 Introduction

In 1929, Hans Berger first demonstrated the possibility of recording brain activity from an intact human skull using crude, early instrumentation later called electroencephalogram (EEG) (Berger, 1931). Observing the complex recorded traces of the electrical signals, Berger recognized spontaneous oscillations, particularly over the occipital area of the cortex in the back of the head. He called these spontaneous oscillation *alpha waves*. Berger had no clear interpretation of the nature of such oscillations or what they represented of the human mind, but he opened a new methodology for the exploration of the human brain.

During succeeding decades, numerous other scientists reported various methods of extracting information from the brain using the EEG, such as analyzing other brain regions with lower amplitude activity and charting the whole spectrum of possible brain signals. Their intent was building a taxonomy relating human condition to specific brain frequencies for interpretation and diagnosis.

In a now-famous 1934 paper, the pioneering physiologists E. D. Adrian and B. H. C. Matthews reported experiencing translation of the human EEG into audio signals. While listening to his own alpha rhythm presented through a loudspeaker, Adrian tried to correlate his subjective impression of hearing alpha waves come and go with the activity of looking or not looking with his eyes (Adrian and Matthews, 1934).

The use of auditory translations of EEG patterns allowed observers and investigators to employ considerable integrative powers of auditory perception to guide them toward some insight into the form of brain signals. Today, the scientific field of sonification investigates how to aurally translate complex number sequences, such as code bugs, star movements, and earthquake signals. Listening has proven to be an helpful and intuitive way to extract local relevant properties from large and complex signals that might otherwise go undetected. We also live in a fantastically rich contemporary music milieu in which, as musicians, our ears are evolving even greater powers to help us manage sometimes immense and deep formal architectures. What we may yet discover by listening to our own brain is still unfathomable.

Throughout the history of advances in science and technology, artists have always been ready to experiment with applications of each new breakthrough or development, almost as soon as it is conceived or realized. Brain science proves no exception. About half century ago, composers like Alvin Lucier, Richard Teitelbaum, and David Rosenboom produced major works of music with EEG and other bioelectronic signals. After two decades of stagnation, new artistic impetus currently in the field of brain music is again pushing towards new directions. These new artistic productions can take advantage of the computational powers that make possible the real time calculation and sonification of brain signals possible. Consequently new and sophisticated statistical and analytical methods for brain analysis are also available.

1.1 Motivation for electronic music from EEG

Since the discovery of electric pulsations arising from within the human brain, imaginative souls have speculated that internal realities would eventually be made externally and materially manifest through a direct connection of the brain to devices for sound production and visual display. Moreover, the connection of the brain with engines or actuators gives the idea to have telekinetic control at hand's reach.

The strive to thought control, unleashing the unknown powers of the mind to affect change in the material world, is an ancient human desire embodied in myths and magic characters. Very often technology is directed to partially overcome the boundaries of our physicality, translating ideas into actions and freeing us from the burden of gravity. The evolution of mankind can be interpreted in this light as a strive to reduce progressively the body effort through a higher hierarchical intellectual control that can be taken to its direct consequences and ultimately achieved only though the understanding of our own brain functionality. However in a paradoxical loop it seems that light can be shed on our brain only through observation and translation of its activity in a sensorial, thus material form. These expectations of reaching telekinetic control transform the EEG into a symbolic tool invested by the mystical power of unveiling of the obscure inner self, the invisible secrets enclosed in the brain and in our subconscious, able to reveal ourselves and the other through what we have commonly hidden inside of us from the very beginning of our existence.

Translating such a paradigm into music is just the next intuitive step. Since our past, music is often connected with sacred celebrations in primitive cultures and still in rituals and ceremonies in modern societies, so impalpable and evocative that seems the perfect tool to tell about the inner gods and symbols. Music seems to have the complexity to represent the intricate brain signals. Being the most transient of the arts, music crosses the delicate bridge between materiality and immateriality, between the body and the soul, and can transpass from the discrete electrical signals to the complex invisible mind realm.

The immateriality of music brings a degree of abstract symbolism that leaves the listener free to float, imagining the connections between musical events and brain signals, interpreting personally what is happening in the brain. In this sense electronic music is just the natural choice as the EEG detects the signal electronically.

In our wildest speculation, our internal realities would become enfolded through the senses into an evolving interplay among the fabricated models of cognition, the passages of consciousness, and the energetic, though capricious, environment. A global music, reflecting the morphodynamic holarchies of existence, might come into being.

We are still far from such a possibility. After almost a century of studies the mind is not much clearer than before, and music applications struggle to find ways to display the brain signal for the audiences. The telekinetic powers are limited and difficult to represent in an artistic form, for a large audience. The telekinesis that allows the dematerialization of the gesture is at the same time the main cause of invisibility of what happens and what can be visualized and transmitted to an observer. Finally the brain is not a simple muscle, finding ways of creating consistent brain states in the form of electrical signals is a difficult long process that is rarely successful. Because of the technical difficulties of harnessing the brain, very often the expressive possibilities of performers are still quite limited, hence the field of EEG art is slowly evolving, rarely proposing artworks with surprising and new contributions.

The aim of the present research described in the rest of this thesis is to explore the potential of brain signals, extracted using electro the EEG sensors, for artistic applications. I intend to analyze the aesthetic advantages ad expressive limitations of such tool and consider which artistic consequences it brings on stage in the case of a brainwave live performance. These aspects are important for the composer to permeate the EEG sensors with a poetic and metaphoric function and create a performance that is more than a mere scientific demonstration. At the end I will explain my personal approach to solve some of the technical and theatrical issues that are intrinsic of such a system that I used in my performance *"Fragmentation"*. The aim of this thesis is to propose thematics for reflection for contemporary and future composers. I will analyze aspects that I consider fundamental for the creative process of EEG performances not only from a technical perspective but also on a dramaturgical level, considering the impact of magic and invisibility on stage for the audience.

2 General Concepts

Before proceeding further it is important to introduce some fundamental concepts of neuroscience, basic terminology and definitions that will be useful for the rest of the thesis. The concepts presented keep in line with the aims of the thesis. Specifically, the concepts will relate to how a system for extracting meaningful semantic information from brain signals can be built for practical and simple music applications and performances.

2.1 The brain and the mind

The main protagonist of this thesis is the brain, the center of our nervous system, as in all vertebrate and most invertebrate animals (only a few primitive invertebrates such as sponges, or jellyfish do not have one). The brain is commonly described as the most complex organ in our body. The cerebral cortex, the largest part of the brain, contains from 15 to 33 billion neurons (Pelvig et al., 2008), each connected by synapses to several thousand other neurons. The neurons communicate by means of long fibers called axons, which carry signal pulses to distant parts of the body for different physiological purposes.

The brain exerts control over the other organs of the body in two ways: generating patterns of muscular activity, and through hormonal secretion. This centralized control allows fast responses in reaction to changes in the environment. Some basic types of responsiveness such as reflexes are enacted by the spinal cord, but sophisticated control of body behavior requires the capabilities of a centralized brain.

What makes the brain so special in comparison to other organs is that it constitutes the physical matter for the mind. The mechanisms by which brain activity gives rise to consciousness and rational thought have been very challenging to understand. Despite recent scientific progress, the deep aspects of our self-awareness are still very difficult to explain and model (Tononi, 2008).

The functions of the brain and the mind depend on electrochemical signals. Neurons respond to signals received from other cells and transmit modified signals again. The electrical properties of neurons are controlled by a variety of biochemical and metabolic processes in the synapses. As a side effect of the electrochemical processes used by neurons for signaling, the brain tissue generates electric fields when it is active. Most of the different methodologies used to analyze and explore the brain activity and behavior measure the electrical potentials of the neural processes to assess reactions to stimulations. The electrical signal obtained in this way can be digitalized and used for analysis of for several control purposes, such as music synthesis.

2.2 Measurement techniques

Because the electrical signal of the brain is extremely weak, one common objective to all measuring techniques is to maximize the signal to noise ratio. With respect to measuring electrical potentials from the brain, the signal is the variation of the electrical brain activity over time, while the noise is provoked by the external sources such as environmental electricity, such as head muscle activity potentials, movement artifacts, and so forth.

Methodologies can be subdivided into two main families: invasive and non-invasive techniques. Invasive techniques attempt to maximize the signal to noise ratio by the direct measurement of the electrical potentials from the brain matter itself. Electrocorticography is an example of invasive procedure using electrodes placed directly on the exposed surface of the brain to record electrical activity from the cerebral cortex. A craniotomy (a surgical incision into the skull) is required to implant the electrode grid. This methodology is currently considered to be the best way for defining epileptogenic zones in clinical practice. These methods are rarely applied on humans because of the danger introduced by the invasive techniques.

The non-invasive techniques measure the brain activity without direct contact with the brain, typically consisting in Magnetic Resonance Imaging (MRI) and electroencephalography (EEG). Despite the advantage of non altering the brain structure, thus being much less dangerous for the subject than the invasive techniques, these techniques suffer of smaller signal to noise ratio. Hence making more difficult the extraction of reliable brain information.

An MRI machine uses a powerful magnetic field to align the magnetization of some atoms in the body, and radio frequency fields to systematically alter the alignment of this magnetization. This causes the nuclei to produce a rotating magnetic field detectable by the scanner and this information is recorded to construct an image of the scanned area of the body.

2.2.1 Electroencephalography

When large numbers of neurons show synchronized activity, the electric fields that they generate can be large enough to be detected outside the skull, using EEG

(Misulis, 1997; Singh, 2006). These electric fields are nevertheless extremely faint, with amplitudes of the order of only a few microvolts. To be displayed or processed, these signals must first be amplified.

EEG is measured as the voltage difference between two or more electrodes on the surface of the scalp, one of which is taken as a reference. Normally, this reference is an electrode placed in a location that is assumed to lack brain activity, such as the earlobe or the nose. It is also common practice to calculate EEG of an electrode by averaging the signal from all electrodes and then subtracting it from the signal of each electrode for normalization.

In clinical contexts the brain's spontaneous electrical activity is recorded over a short period of time, usually 20-40 minutes, using multiple electrodes placed on the scalp. In neurology, the main diagnostic application of EEG is in cases of epilepsy, as epileptic activity can create clear abnormalities on a standard EEG study. A secondary clinical use of EEG is in the diagnosis of coma, encephalopathies, and brain death. EEG used to be a first-line method for the diagnosis of tumors, stroke and other focal brain disorders, but this use has decreased with the advent of anatomical imaging techniques with high (<1 mm) spatial resolution such as MRI.

The characteristics EEG has made it the preferred choice over the MRI methodologies for the sonification of the brain signals and for artistic applications using brain data. The MRI technique requires perfectly static subjects to acquire the imaging, imply a large cost for the devices applied, which can typically be covered only by rather large medical institutes or companies, and it's a non real time procedure because requires it has to be performed before the scan can be visualized. Furthermore EEG sensors can be displaced and used in different locations, as opposed to the bulky fMRI machine. The EEG has higher temporal resolution (milliseconds, rather than seconds), is relatively tolerant of subject movement, is silent, which allows for better study of the responses to auditory stimuli, does not aggravate claustrophobia, does not involve exposure to high-intensity (>1 Tesla) magnetic fields (as in MRI). For these reasons this thesis chose the EEG and its signal for possible applications of brain music.

2.3 The brain signal

In analog EEG, the signal is output is shown via deflection of pens as paper passes underneath. Digital EEG is similar with amplitude values (samples) written in a computer memory progressively. Regardless of how the signal is captured, what we obtain is a recording of the brain activity with the intensity of the electrical activity on the $y-axis$ displayed versus time on the $x-axis$. Following the forms of the oscillations, a trained neurologist can visually identify brain malfunctions or predict seizures. Each part of the brain shows a mixture of rhythmic and nonrhythmic activity, which determine the form of the brain signal. During an epileptic seizure, the brain's inhibitory control mechanisms fail to function and electrical activity rises to pathological levels, producing EEG traces that show large wave and spike patterns not seen in a healthy brain.

The EEG is a difficult signal to handle because it is impeded by the meninges (the membranes that separate the cortex from the skull), the skull, and the scalp before it reaches the electrodes. The signal is structure is that of a stochastic time series with almost stationary epochs of various lengths separated by sharper transitions or disruptions. Amplitudes are small and spectral decomposition reveals that little power remains above 30 Hz. Most of it is contained at very low frequencies and within the narrow bands of specific rhythms that appear and disappear somewhat randomly in time. Signals collected on two or more electrodes exhibit changing levels or correlation, due to either physical proximity, or actual coordination between cortical sites, thus reflecting share neural activity within the brain itself.

This signal must be further scrutinized with signal processing and analysis techniques in order to be of any use for our research. There are three fundamental approaches to EEG analysis: 1) power spectrum analysis, 2) event-related potential analysis, and 3) hjorth analysis.

2.3.1 Power spectrum analysis

Spectral analysis use the technique of Fourier transformation to extract the signal energy in different frequency bands thus identifying what we call brain rhythms or brainwaves. The energy in each spectral band defines the relevance of each brain rhythm for a precise moment in time. From general observation we can categorize the different rhythms and associate them to specific brain states or activities.

- Delta (δ) is the frequency range up to 4 Hz. It tends to be the highest in amplitude and the slowest. It is seen normally in adults in deep sleep. It is also observable in babies.

- Theta (θ) is the frequency range from 4 Hz to 7 Hz. It is normally seen in young children, or in drowsiness and arousal in older children and adults; it can also emerge during meditation and deep dreaming phases.

- Alpha (α) is the frequency range from 8 Hz to 12 Hz. Hans Berger, the first man performing an EEG in 1921 (Berger, 1931), named it alpha because it was the first rhythmic EEG activity ever observed. It emerges with closing the eyes and in relaxation, and attenuates with eye opening or mental exertion.

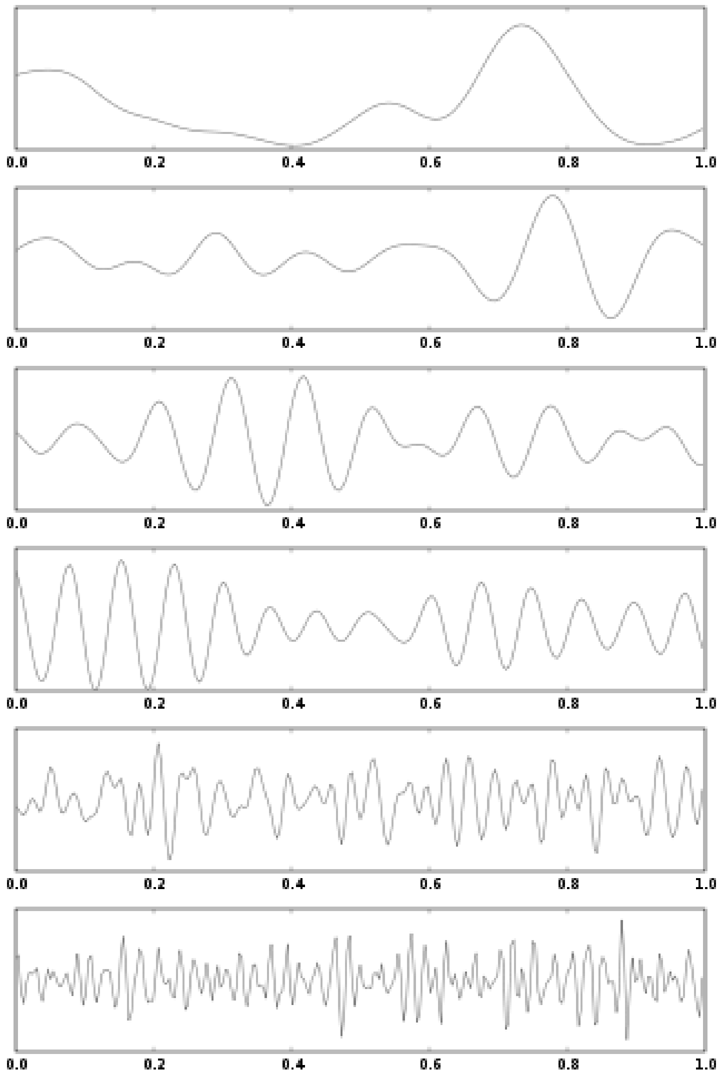

Figure 2.1: Example of brainwaves. From top to bottom: delta, theta, alpha, mu, beta, gamma. The *x-axis* displays time in seconds while the *y-axis* shows the signal amplitude in arbitrary units

- Mu (μ) ranges from 8 to 13 Hz, and partly overlaps with other frequencies. It reflects the synchronous firing of motor neurons in rest state.

- Beta (β) is the frequency range from 12 Hz to about 30 Hz. It is seen usually on both brain sides in symmetrical distribution and is most evident frontally. Beta activity is closely linked to motor behavior and is generally attenuated during active movements.

- Gamma (γ) is the frequency range approximately between 30 and 100 Hz. Gamma rhythms carry out complex cognitive and motor functions.

The most complete and easiest way to observe the brain signal is through a spectrogram, which displays the evolution of the brain spectral energy over time.

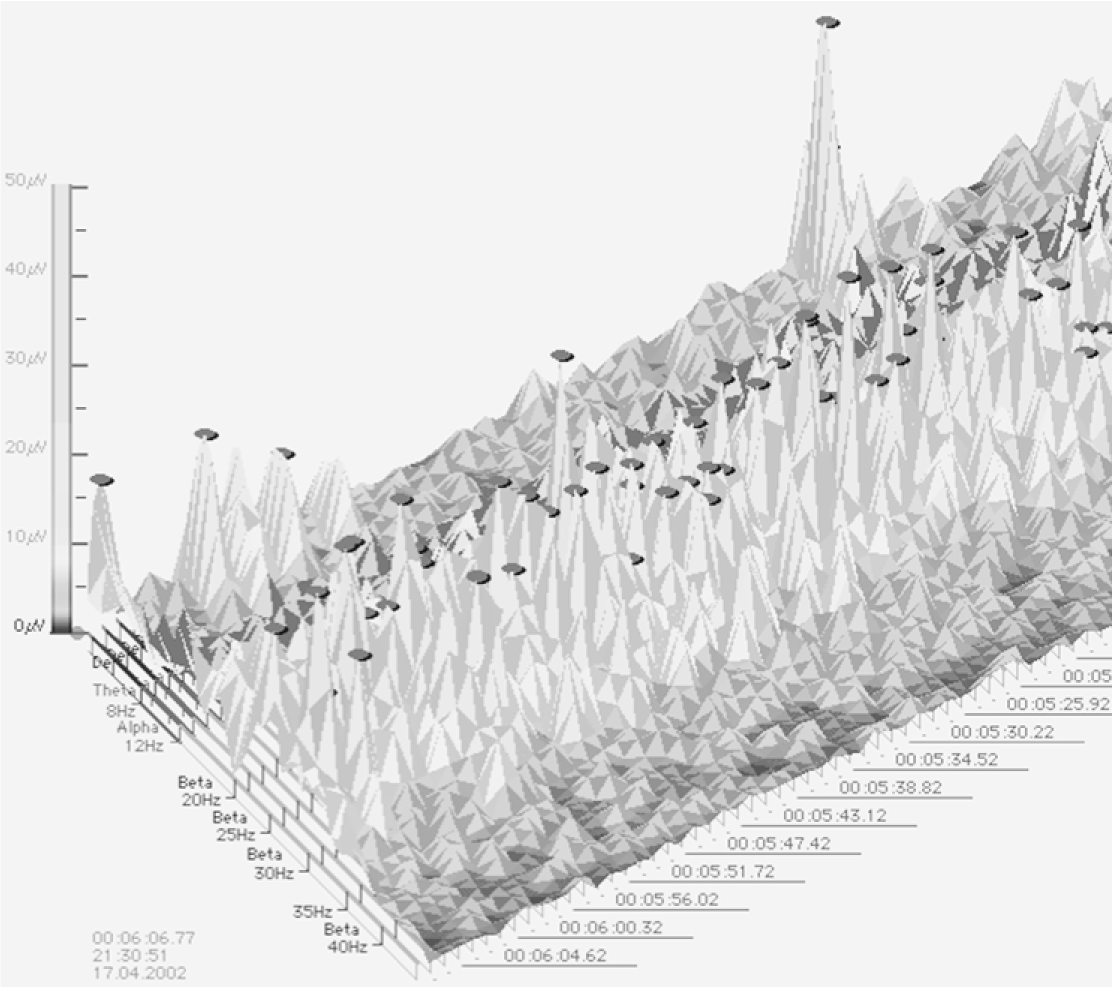

Figure 2.2: Example of brain spectrogram showing the frequency content over time. The *x axis* (on the right part of the figure), displays time, the *y axis* (on the left) reports the frequency content, and the *z axis* (vertical) represents the intensity. The high presence of beta and gamma waves is clearly visible, probably representing a state of wake and attention. Image courtesy of Miranda et al. (2003).

2.3.2 Event-related potential analysis

An event-related potential (ERP) is any measured brain response that is the direct result of thought or perception. Usually it is any electrophysiological response to an internal or external stimulus. Experimental psychologists and neuroscientists have discovered many different stimuli that elicit ERPs from participants. The timing of these responses is thought to provide a measure of the timing of the brain's communication or time of information processing. For example the first response of the visual cortex is around 50-70 msec: this would seem to indicate that this is the amount of time it takes for the transduced visual stimulus to reach the cortex after light first enters the eye. Alternatively, the P300 response occurs at around 300ms in the oddball paradigm, for example, regardless of the stimulus

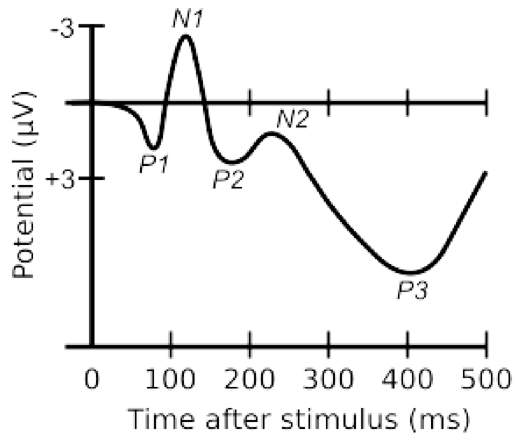

Figure 2.3: Example of a Event-related potential

presented: visual, tactile, auditory, olfactory, gustatory, etc. ERP is understood to reflect a higher cognitive response to unexpected or cognitively salient stimuli because of its general invariance in regard to stimulus type.

2.3.3 Hjorth analysis

Hjorth analysis is an alternative analytical method to investigate the timing aspects of the signal. Using a combination of the first and second signal derivative, this method assesses how mobile and complex is the signal in time, to observe how much statistical variation occurs between one sample and the next and which kind of intervallic jumps are present. It measures three attributes of the signal: its activity, mobility and complexity. Activity is the variance of the amplitude fluctuations in the signal window. Mobility is calculated by taking the square root of the variance of the first derivative divided by the variance of the primary signal. Complexity is the ratio of the mobility of the first derivative of the signal to the mobility of the signal itself (Hjorth, 1970).

2.3.4 Artifacts

Most of the brainwave signals contain artifacts, which are spurious signals that do not strictly depend on the brain activity and alter the normal shape of the brainwave. It is important to be able to recognize and eliminate them for the correct interpretation of the EEG data. In general, artifacts have longer waveforms than the normal rapid oscillations of the EEG signal, so it is quite easy to identify them. Usually we can distinguish artifacts into *biological*, provoked by eye movements or muscular activation in the scalp, and *environmental*, induced by magnetic fields connected to electrical apparatus close to the EEG device.

For artistic purposes artifacts can be turned into useful signal markers, as opposite to scientific research which generally requires their removal or reduction.

Artifacts can be identified easily and used to trigger events or preset changes in the composition or in instrumental control (Arslan et al., 2005; Hinterberger, 2007).

2.4 Brain Computer Interface

Jacques Vidal first introduced the terminology of Brain-Computer Interaction (BCI) in 1973 (Vidal, 1973). In a visionary article he posed the fundamental question that we are still trying to answer nowadays:

> "Can these observable electrical brain signals be put to work as carriers of information in man-computer communication or for the purpose of controlling such external apparatus as prosthetic devices or spaceships?" (Vidal, 1973)

Vidal illustrates the laboratory setup used to investigate such a possibility and experiments to approach the solution of such problem. A little less than 30 years after a typical medical laboratory has more or less the same apparatus, disregarding the obvious difference in computer power and digital memory involved in the laboratory.

The EEG recording is obtained by placing electrodes on the scalp with a conductive gel. Most systems use caps or nets into which electrodes are embedded; this is particularly common when high-density arrays of electrodes are needed. Each electrode is connected to the input of a differential amplifier (usually one amplifier per pair of electrodes). A common system reference electrode is connected to the other input of each differential amplifier. The voltage amplification between the active electrode and the reference is typically 1,000-100,000 times, reaching 60-100 dB of voltage gain. Most EEG systems these days, however, are digital, and the amplified signal is digitized via an analog-to-digital converter, after being passed through an anti-aliasing filter. Analog-to-digital sampling typically occurs at 256-512 Hz in clinical scalp EEG. Considering the Nyquist theorem this is largely enough to detect from theta to gamma waves, as the detected spectrum in this case goes from 0 to 128-256 Hz. Typical settings for the high-pass filter and a low-pass filter are 0.5-1 Hz and 35-70 Hz, respectively. The high-pass filter typically filters out slow artifact, such as electrogalvanic signals and movement artifact, whereas the low-pass filter filters out high-frequency artifacts. An additional notch filter is typically used to remove artifact caused by electrical power lines.

It is quite easy to imagine how adding peripherals for artistic purposes might extend the scientific setup. Very often a sound module is connected to the computer for brain sonification to attract the attention of the doctor in case of anomalies. Also, other modules can be connected to let the brain signal control, for example visuals or mechanical engines. The typical setup of an electronic musician is quite similar: a controller or sensor device, cables, an acquisition card, a computer for sound processing, and a sound card for the sound generation. It is quite natural to just substitute a controller with the EEG sensor cap, connect the incoming signal to a digital synthesizer and try to make some sounds. Such a general system architecture has been called Brain-Computer Music Interface (Miranda and Brouse, 2005).

The BCI systems require also a software part that is responsible of extracting the information from the brain signal to be used in the specific application. The software aspect has evolved through the years, especially thanks to the recent mathematical models for digital signal analysis and classification. We can distinguishes three possible categories of BCI systems: Computer Oriented systems and User Oriented systems and mutually oriented systems (Kubler and Muller, 2007). In *user-oriented BCI systems*, the computer adapts to the user. Metaphorically speaking, these systems attempt to "read" the mind of the user to control a device. For example, Anderson and Sijercic (1996) reported on the development of a BCI controller that learns how to associate specific EEG patterns from a subject to commands for navigating a wheelchair. The prosthetic hand and the monkey experiment mentioned earlier also fit into this category. With *computer-oriented BCI systems*, the user adapts to the computer. These systems rely on the capacity of the users to learn to control specific aspects of their EEG, affording them the ability to exert some control over events in their environments. Examples have been shown where subjects learn how to steer their EEG to select letters for writing words on the computer screen (Birbaumer et al., 1999). Mutually-oriented BCI systems combine the functionalities of both categories, where the user and computer adapt to each other. The combined use of mental task pattern classification and biofeedback-assisted online learning allows the computer and the user to adapt. Prototype systems to move a cursor on the computer screen have been developed in this fashion (Peters et al., 1997). Coevolving systems of humans and computers belong in this category. As we will see most of the proposed works of music using EEG signal use computer-oriented systems. The performer has to learn from the system, typically using spectral analysis to produce the correct wave frequencies to trigger some reaction. Future artists can be inspired by the other two categories and examples from the BCI literature and translate these more complex systems into BCMI to test if more controllability can be achieved.

3 Historical Context

It is almost impossible to discuss the subject of brainwave music without mentioning the first pioneering experiments by Alvin Lucier, David Rosenboom and Richard Teitelbaum. Between the late 60s and early 70s these composers attempted to control brainwave signals to create music. Each one of these composers used EEG signals in a personal way, reaching different musical and performative results.

After an initial outburst that lasted through the 70s, music production in connection to brainwaves suddenly stopped during he 80s and 90s. This phenomenon is surprising considering the large diffusion of personal computers during the 80s and 90s, which offered the possibility to deepen the exploration and analysis of digitalized brain signals. Research into brainwave music restarted in the beginning of the new millennium, with the idea of using new statistic tools and digital signal processing (DSP) techniques for signal analysis and interpretation.

Recently a small-scale revolution has been going on, which is connected with the availability of cheap EEG headsets on the market. Cheaper headsets means lower costs for even independent artists, who can now experiment with EEG signals without support from funds or medical laboratories.

3.1 The first experiments

3.1.1 Music for solo performer

In 1965 Alvin Lucier performed the first piece in history using brainwave to produce sound: *Music for solo performer.* The piece holds on two main ideas:

- alpha waves, which have a sub-audible frequency range between 8 and 13 Hz, could be made audible if amplified enormously and channelled through an appropriate transducer,
- alpha waves could be triggered by closing or opening the eyes. The control of the alpha waves depends on the control of the thought content and can be done without involving any part of the body motor system.

In *Music for Solo Performer*, no complex EEG detection or analysis tools were needed. A simple EEG band with one to three sensor can be placed around the frontal lobe of the performer to detect the required signal. The main difficulty resides in tuning the system to obtain a clean signal, strong enough to be separable from the background noise. This is especially true in the case of noisy analogue devices, such as the ones used by Lucier in the 60s (Collins, 2009). The final sound of the piece depends on the composer's choice of transducers, like coupling the loudspeaker to percussions, modifying resonating surfaces, inserting strange materials like scrap, marbles, or rubber balls into the loudspeaker cone. It is the task of an assistant to channel the input alpha signal to the different output loudspeaker/transducer systems, effectively deciding the structure and character of the whole piece. Performances have no pre-determined length and historically several experiments have been done in this manner. Also transducers have sometimes been replaced by switches to activate radios, television sets, lights, alarms and other audio-visual devices (Lucier, 1995).

Many aspects make *Music for Solo Performer* a revolutionary and peculiar piece. Most important is the choice on how to sonify the brain signal. The human ear can perceive sounds from 20 to hypothetically 20,000 Hz (even though most people would not reach 17.000 Hz due to deterioration of ear cells during their lifetime) (Moore, 2003). The previous chapter showed how most of the energy of the brain's electrical activity lies in the sub-audio range, the prominent alpha rhythm being in the range 8-13 Hz. The most intuitive option to translate this signal into sound is to record the EEG on tape and then to speed it up. Having obtained an audible signal it is easy at this point to fall into temptation of adding a filter, passing the signal through a reverb box, or applying all kinds of other effects. This would alter the nature of the brain signal however, which is what the composer originally wanted to present. Moreover, this recording process would of course eliminate the possibility of a live performance. A recording would present just another tape piece with material that could have been previously manipulated and pre-controlled and would have no direct, instantaneous connection with the living activity of the brain on stage. Alvin Lucier realized the bigger theatrical impact that brain control has during a performance compared to the musicality of brain signals used in a tape piece. Lucier accepted the sub-audio nature of his material, and tried to represent it in its original form:

> "At the time we were concerned with letting the sounds to be themselves, so I don't think by cutting and pasting I would have let the alpha be itself." (Lucier, 1995)

Following this reasoning it seems a natural choice to use drums as an instrument to be coupled with the loudspeakers as shown in the score schematics: drums do not need pitches exactly as the alpha brainwaves become just a rhythm in their

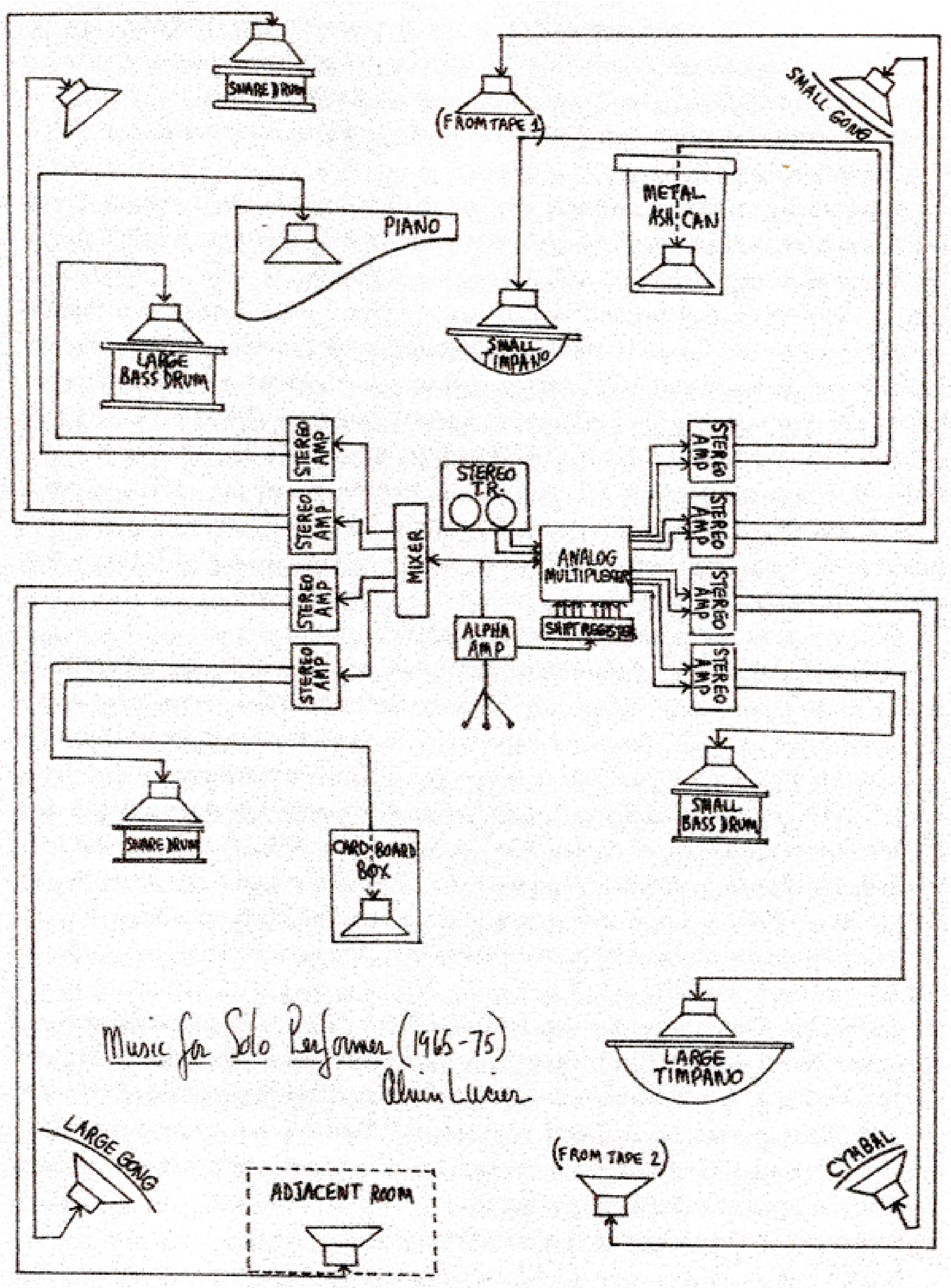

Figure 3.1: Scheme for *Music for Solo Performance* drawn by Alvin Lucier to illustrate the suggested connections for the performance.

sub-audio range (Stockhausen, 1957) [1]. Lucier himself expressed his preference for unpitched material:

> "To make it a pitched piece would seem to me grotesque or bizarre." (Lucier, 1995)

The choice of presenting his piece as a live performance carried several consequences, which included the non-manipulation brain signals. Bringing the EEG production on stage enriches the poetic beauty of the artistic act by allowing the audience to directly experience the brain activity of the performer. The difficulty of producing the required signal creates involvement from the audience through tension and expectation. A live piece shows the whole instability and fragility of our mind. The small changes of the performer's facial expression become magnified and the audience tries to read into these changes to predict the internal tension of the performer whilst justifying it against the nature of the musical output. The atmosphere during such a performance is described by Pauline Oliveros:

> "When I first saw Alvin Lucier for the first time I was struck by the charged atmosphere, as if the expectations or the curiosity of the audience become palpable." (Oliveros, 1984)

In such performance the performer must come to terms with his/her own consciousness in order to perform the piece. With this performance Lucier pointed the way for an extremely important trend in today's music: not only one should play the correct notes at the right time but also have the right consciousness and feeling of the piece.

Another important aspect is connected to the telekinetic metaphor, the possibility to move material objects with the sole power of the mind, and the socio-political impact of it related to the philosophical context of the 60s and 70s. When talking abut how Lucier was seen during those times, Nicholas Collins described him as a

> "... poet-wizard able of creating a beautiful sound without physical force, without striking any stick on a drum skin, or using contact with matter'.' (Collins, 2009)

The possibility of exerting force to move loudspeakers and produce sound without direct contact, bypassing the body entirely, must have presented an appealing metaphor in the view of the anti-aggressive philosophies connected to the hippie movement of the 60s and later in the 70s with the Viet-nam war. The telekinetic possibility evoked by *Music for Solo Performer* brings also a fresh perspective on the sound itself: where lies the sound if it translates shape from electricity to air

[1] It is also a common terminology in neuroscience to call the brainwaves *"brain rhythms"*.

pressure, and then that air pressure activates some physical reaction that creates sound again? Is the sound the energy in the whole instrumental chain or just the audible result of it? The role of the loudspeaker changes from sound generator to physical actuator; the sound itself assume the new role of a physical force. A sound chain between invisible through visible, between inaudible to audible. The thought seems to be translated into sound. Lucier's work is so new ad evocative that we find ourselves having to revise our basic and often unconscious assumptions, our self-evident axioms, about music. As Tenney said:

> "Before that performance nobody would have thought it necessary to define the word music to account for such a manifestation, but that performance become rapidly a classic, making a redefinition of music necessary." (Tenney, 1988)

An important point is the use of the technology and the relationship between the poetic of the piece and the instruments used, as *Music for Solo Performer* was probably the first piece in history that put a scientific medical device into the concert hall and made it protagonist. The EEG sensors bring a decontextualization on stage and a new perspective. What is happening, is it a scientific experiment, a public measurement, a sort of sonification or a visual performance? We know from the other production of the author, that technology is employed by Lucier in a very different way than in most other music: to reveal some aspects of nature, through resonation, feedback, beatings, reflections, diffraction, and standing waves. In most of his pieces we hear the interaction of a natural system and a technological one. And because of its intrinsic difference in behavior the results are so interesting, varied, and unpredictable. In the case of the *Music for Solo Performer*, the resonation happens within the human himself, being both natural ad technologic in its essence, listening to the outside result of his/her internal state, confronting concentration and the distraction. As Lucier pointed out:

> "The problem was to stabilize the concentration to have alpha waves enough to be able to compose or create sound with it." (Lucier and Simon, 1980)

As a consequence, there could not be any score for such a composition, the score is the performer's consciousness at the very moment of the performance.

> "I let the structure go, let the continuity of the alpha pulses, as they flowed out of my head, determine the moment-by-moment form of the performance. Somebody suggested to record the alpha waves and compose the piece, but then I decided to do it live, and that's a risk because it's not sure you can get them, the more you try the less

> likely is to to succeed. So the task of performing without intending to, gave the work a irony it would not have had on a tape." (Lucier and Simon, 1980)

In *Music for Solo Performer* the figure of the performer is very contradictory and maybe it is this contradiction that makes the performance also extremely evocative. The first striking aspect is that the performer cannot move because if he moves, he loses the alpha waves, and hence the sound.

> "One of the main aspects I think was the apparent passiveness of the performer actively making music and making so many objects vibrate." (Oliveros, 1984)

A second obvious contradiction lies in the very title of the piece. As Lucier admits:

> "It's not really for solo performer, you need another person to run the amplifiers, to pan the sounds around, to turn on one loudspeaker, and then turn on another." (Lucier, 1995)

One can even argue that the real performer is who Lucier calls *"the assistant"*. It is in fact the assistant who decides the structure and duration of the piece, which instruments to combine, and all transitions. Lucier does not have much control on the piece. He is responsible to produce its driving energy, similarly to a power generator. Lucier himself also suggests in the score the possibility to

> "Design automated systems, with or without coded relays, with which the performer may perform the piece without the aid of an assistant." (Lucier, 1995)

.

Following the previous reasoning, in this extreme case a more appropriate title would then be *"Music with No Performer"*.

Another contradiction lies in the production of the actual brainwaves because the whole chain of signal could be disturbed by internal noise or electrical failure, Lucier suggests in his own score:

> "To use switches which activate one or more tape recorders upon which are store pre recorded alpha." (Lucier, 1995)

He also reported:

> "So I did use pre-recorded tapes and I did use alpha as a control signal, but they were used as extensions of the idea and were not the essential idea ... I had pre-recorded brain waves sped up into the audio range, and at certain times during the performance, I would have an assistant engage a switch that, as a burst of alpha waves came through the tape recorder, would switch on and you'd hear a higher phantom version of the alpha." (Lucier and Simon, 1980)

Despite all the claims by Lucier on the importance of a live act, it is not clear how much *Music for Solo Performer* really relies on actually live-produced alpha waves, or on pre-recorded material. This question becomes perhaps irrelevant when we consider the whole performance as a sort of a magic show in which the audience wants to believe and the task of the artist is then to create the conditions for such generalized illusion. Lucier seems to have the poetic nature and the character to evoke such a magic atmosphere.

3.1.2 In Tune

Between 1966 and 1974 Richard Teitelbaum produced several brainwave performances, of which *"In Tune"* was most performed. Teitelbaum used a different approach from Lucier to sonorize the sub-audio brainwave signal. In those years Robert Moog was known in the music world for the principle of voltage control. He used the signal voltage to manipulate the parameters of a synthesizer. Teitelbaum had the idea to extend this concept of introducing brain activity of a performer in the synthesizer's architecture by letting the EEG signal directly modify the sound parameters, while the composer can freely improvise with higher structural decisions. This idea was a part of a larger project:

> "Orchestrating the physiological rhythms of the human body, heart, breath, skin, muscle, as well as brain, with the whatever material from the vast gamut of electronic music was an exciting one, both musically and psychologically." (Rosenboom and Teitelbaum, 1974)

One of the central direction of Teitelbaum's exploration was the idea of creating a closed loop involving brainwaves and sound. He had derived the idea from a realistic dream he had on the summer of 1966. With this idea, the performer would generate brainwaves that would be processed and translated into sonic domain by the composer. The translated brainwave would then travel back to the ears of the performer and translated back into electrical brain signals. What would the signal of such a loop sound like? In this respect, the idea of connecting the brain to a synthesizer, instead of moving acoustic drums as in *Music for Solo Performer*, seemed even more appropriate. The resultant electronic sounds available would offer many possibilities to find efficacious sonic material to affect the performer's consciousness in the feedback loop.

The first output of Teitelbaum's sonic experiment was *Spacecraft*, a group improvisation of the collective Musica Elettronica Viva, of which Teitelbaum was part. The improvisation used no score, instead each musician carried on an inner search through the recesses of his own consciousness. As the composer describes, the composition used:

> "Electronic instruments (contact microphones, synthesizers, etc.) into highly amplified sounds fed back from spatially distant loudspeakers, and electronically transformed *"double"* mirroring the performer's internal state." (Zimmerman, 1976)

In these performances, Teitelbaum employed the neuro- and physiological signals of his own body as real time musical materials, using heartbeat, chest cavity and throat contact microphones as transducers, as well as electrodes for EEG and EKG (electrocardiogram). All these signals were driving parameters of the Moog synthesizer.

Organ music, was presented in 1968 with saxophonist Steve Lacy supplying brainwaves, Irene Aebi, for the heartbeats, and Teitelbaum controlling the Moog and mix. In this case the composer used not only the alpha waves, but also the whole EEG spectrum to control the frequency, amplitude and filtering of four oscillators. Several loudspeakers were distributed around the space to give to the audience the impression

> "... of being inside a living heart and brain." (Rosenboom and Teitelbaum, 1974)

.

The last performance of this set of brainwave exploration was *In Tune*, first presented in the American church in Rome with Barbara Mayfield providing the brainwaves. For the first time an oscilloscope was displaying the brainwave signal for the audience next to the performer. The composition started with biological sounds, recognizable for the audience, such as breathing and heart beats. The performance went then progressively deeper into the performer's body. When the performer closed her eyes, the envelope followers of the Moog system detected the presence of alpha waves and generated loud bursts of sound. The performer played with her eyes controlling the sound emission and created a duet with the composer who had the role of an accompanist, as he modified the sound parameters to support the feedback trance.

The piece was performed several times in different setups. In one of these, the eight-month fetus in the womb of Patricia Coaquette supplied the heartbeat. In another performance, tape recordings of erotic nature were added and live-modified to reach a psycho-sexual meditation space. In yet another, a tape recording containing Tibetan monk chanting was used.

After the initial enthusiasm of experimenting new hardware and sonic possibilities, the charm of brainwave exploration started decaying in Teitelbaum's fascination due to the

> "Contradiction inherent in the idea of performing an inner directed, meditational piece before a concert audience." (Rosenboom and Teitelbaum, 1974)

For this reason *In Tune* was performed another few times before being stopped early in 1970.

3.1.3 On Being Invisible

Among the three early pioneers of brainwave music, Rosenboom is the one that approached the complex brainwave signal in the most rational and logical way. Rosenboom analyzed possibilities, limitations and formalized in several papers how to extract features/descriptors from an EEG signal for the purposes of modeling brain functionalities towards a conscious control of the generative music rules (Rosenboom, 1984; Rosemboom, 1987a,b; Rosenboom, 1990). His investigation not only defined new territories of music exploration with the use of brainwaves and bio-sensors, but also put into question and re-defined the concepts of instrument, psychoacustics and its possible influence into music composition, as well as the impact of the performer's consciousness during the performance.

"On Being Invisible" is the title of David Rosenboom's continuously developing body of work for soloist using EEG sensors (Rosenboom and Teitelbaum, 1974). Its title refers to the role of the individual within an evolving, dynamic environment, who takes decisions of when and how to be a consciously active, and when to simply allow her or his individual internal dynamics to evolve within the system as a whole. A musical metaphor is quickly created: the role of the performer inside a musical composition can sometimes choose to be invisible acting as a resonator, a part of the whole, or at other times, drive the composition towards new directions. This idea led to the creation of a self-organizing dynamic system where the software architecture has to somehow interpret and adapt the compositional strategies of the performerÕs input, in this case through the EEG data. The self-organizing dynamic system works in contrast to fixed musical composition or an improvisation with pre-determined rules. To achieve such an effect Rosenboom built a software architecture that orders the sonic language according to the manner in which the performer prceives sound. He defined the composition and the system an *attention-dependent sonic environment*.

As the author says:

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> “Complete musical forms are constructed as a result of self organizing dynamics of a system in which both ongoing EEG parameters and event related potentials (ERPs), indicative of shifts in selective attention on the part of a solo performer, are analyzed by computer and used to direct the stochastic evolution of an adaptive, interactive music system.” (Rosenboom, 1984)

In the previous chapter, we defined the ERPs, as time-locked reactions of the brain to a stimulus. They can be detected in the brain signal because we know the typical time-delay between the stimulus presentation and its signal reaction. It is common to determine how *“strong”* the reaction of the brain is in connection to a particular stimulus observing the amplitude of the ERP. The assumption of Rosenboom was that we can determine the salience of some musical event, or even how *“interesting”* some musical material is by extracting the performer’s attention in the form of ERPs’ amplitude in the EEG signal.

According to Rosenboom (1990), the functional architecture of such a system would require:

- “(1) a musical structure-generating mechanism coupled to a sound synthesis system;
- (2) a model of musical perception that detected and made predictions about the perceptual effect of various phenomena in an unfolding musical structure;
- (3) a perceiving, interacting entity (human performer);
- (4) an input analysis system for detecting and analyzing bio-electromagnetic and other input signals; and
- (5) a structure-controlling mechanism that directed listed item (1) and updated (2) in response to corresponding information from (4) and (2).” (Rosenboom, 1990)

Rosenboom would require software able to analyze the brain signal; extract the performers’ attention in the form of ERP intensity; and determining’s possible reactions. In a simple example, creating a shift in the musical material when the performer’s attention is not stimulated enough. Such a system uses a threshold on the ERPs’ amplitude that triggers system reactions. This threshold varies dynamically to adapt to the performer’s attention simulating the performer’s familiarization with the material in use.

The visionary research of David Rosenboom went further into the possibility of including a description of the performer’s memory and a model for the expectancy of musical events. These models were conceived using cross-correlation of signals

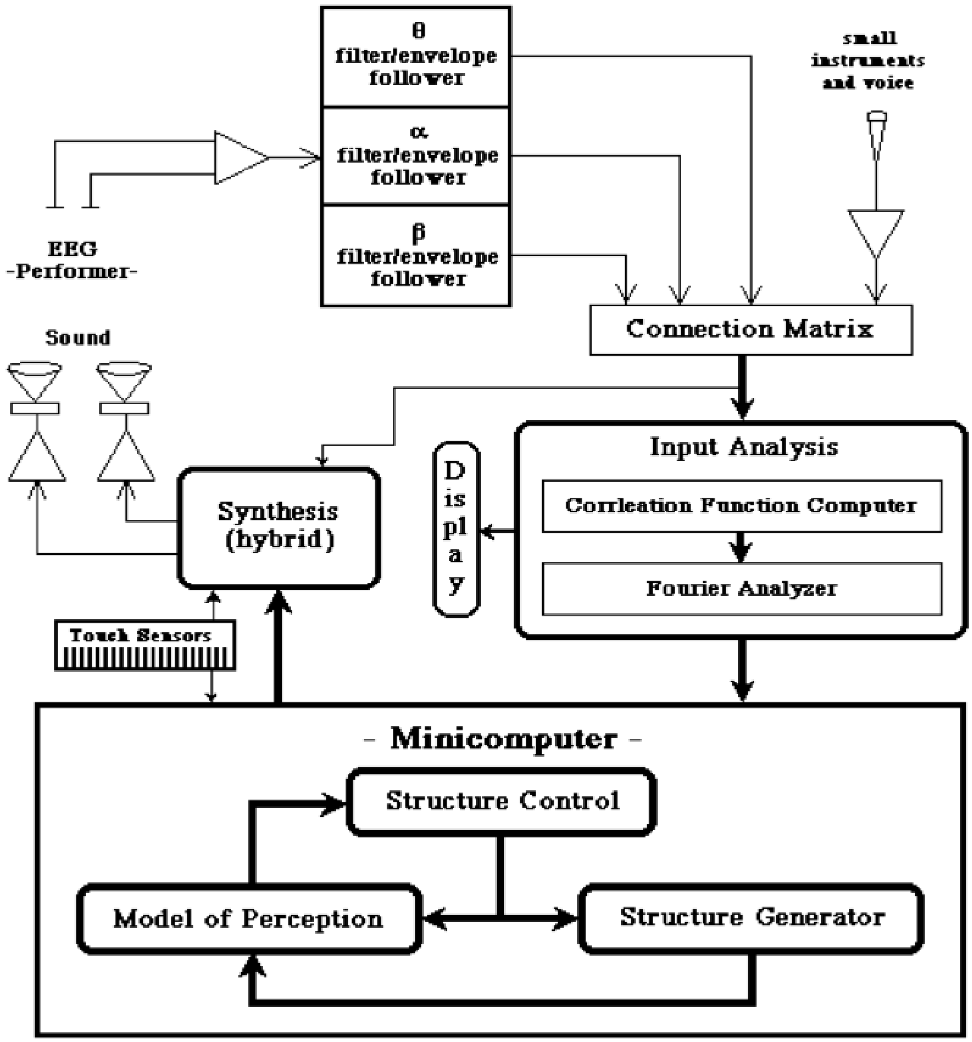

Figure 3.2: Scheme for *On Being Invisible* by David Rosenboom drawn by the composer.

within a stored signal buffer. Cross-correlation can also be used to extract an estimation of the signal's repetitiveness, which in turn reflects stability. Stability might henceforth indicate calmness or boredom in the performer. The complete description of Rosenboom's methodology and implementation goes beyond the purpose of this historical overview but can be found in one of Rosenboom's articles (see (see Rosenboom, 1990)).

It is difficult to describe the sound of such a piece without experiencing it live. From the recording, a sense of change and variation depending on some proportion is evident but difficult to rationalize. Also, I tried to replicate the implementation of Rosenboom's software as described in detail in Rosenboom (1990), but I found it extremely difficult to establish whether my system was really detecting shift of attention in the EEG. The same conclusion is reported after an attempt by Miranda et al. (2003).

The main contribution of Rosenboom's work is the new rational perspective of the problem. By adding an analysis of the EEG signal into the composition, this allows more understanding of the brainwave signal and may lead to the implementation of tools for the conscious control of the music improvisation, or at least to let emerge something of the internal cosmos of the performer. In the case of Lucier's *Music for Solo Performer* and Teitelbaum's *In Tune*, there is no attempt towards a real understanding of the brain. It is treated like a mysterious electrical black box, and as a consequence the performer cannot have any conscious or reliable control on the music. This aspect can be part of the poetic and aesthetic decisions of the composer even though it seems more a like a technologically-imposed limitation than a intentional choice.

Rosenboom's approach and ideas have been the major inspiration for the whole body of research from which this thesis is grounded. For he is the first composer who had a clear intention to understand or decode part of the brain signal, and bring the invisible to visible and the subconscious to conscious. As he says:

> "Though one idea has certainly been that of increasing the palette, bringing previously unconscious processes into conscious awareness and potential use, this work has led to the realization that the stability of natural oscillators is such that one can submerge him/herself in them and learn about the relationship between resonance and the idea of initiating action." (Rosenboom, 1984)

This is not only an extremely challenging poetic strive but also the ground rationale for the extension of brain research into methods of machine learning and pattern recognition.

3.2 The 80s and 90s stop

It is not yet clear why research in brainwave music almost completely stopped during the early 80s until the late 90s. The stoppage came about despite the considerable advantages offered by the increasing computational speed and power, the new algorithms for DSP signal analysis, the statistical models and the availability of larger data storage devices for the purpose of recording EEG data (which was one of the main limitations listed by Vidal in his first experiments in BCI (Vidal, 1973)).

A possible explanation could be the artists' awareness of the complexity of the brain signal after the first enthusiastic experimentations of Lucier and Teitelbaum. Rosenboom's writing made clear the necessity to develop better analytical tools to extract relevant features from noisy EEG signals to achieve new control strategies. This aspect might have seemed too technical and discouraging. However, in the beginning of the new millennium, a new wave of research connecting brain signals and multimedia, branched out toward new investigative fields, such as BCMI and sonification. This new investigation often involved technical personnel from research institutes to cover the required technical aspects of neuroscience and signal processing (Miranda et al., 2008; Arslan et al., 2005; de Campo et al., 2007; Grieson and Webb, 2011).

3.3 Modern diversification: brainwave music, art-science, sonification

3.3.1 Brainwave music for performance and installations

It is possible that the recent availability of numerous affordable EEG headsets on the market boosted the artistic experimentation with brain signals. Most of the companies producing affordable headsets present their products on the market as new controllers for gaming. These headsets are often delivered with software for open-sound-control (OSC) connectivity (CNMAT, 2012), and typically with some esoteric programs for the (usually obscure) estimation of meditation levels and excitement. Personal testing experience rarely showed a clear correlation between software estimation and the user's internal state. It should also be noted that these headsets probably provide poorer signal to noise ratio compared to EEG medical devices, making it even more difficult if not impossible in some cases to detect some real brain activity. It is a legitimate doubt whether some of the hardware really measures anything more than the internal noise of its own sensors.

Contrary to science, art can better accept instability and turn it into an interesting parameter. Contemporary artists have explored different ways of handling the noisy EEG signals or unclear software estimations. With *Sounds of Complexity*, Casalegno and Varriale intend to simplify the complexity of the brain by representing its signals in the form of an audio-visual performance (Casalegno, 2012). They use a series of pre-recorded EEG cerebral activities and use pitch-shifting to translate them into audible frequencies and Cartesian mapping for visualization. Their approach explored what Lucier wanted to avoid in the 60s, which was the recording and transposing of the sound into audible range. The result is visually and sonically interesting but, there is no clear connection for the audience between the signal and what they experience visually and aurally. The lack of a clear connection is because of signal manipulation and because we have no standard idea of how EEG should look or sound like. Also, the visuals and sound of the performance could well have been produced by any other signal, such as meteorological phenomena or star movement. Despite the premises and the artists' objective, the nature of the brain at the end of the performance is no clearer than at the beginning.

To reach more immediacy and the possibility of having a real-time control over brain signals, most artists choose to use EEG signals in live performances (Haill, 2012; Robels, 2012; Chechile, 2012b). Luciana Haill, projected and built her own hardware, which she called the Interactive Brainwave Visual Analyzer (IBVA, 2012). As she explained it in the Wired Web Magazine, in her system

> "the left and right sides of the brain can independently control eight different tracks. It evokes a mysterious atmosphere when you first hear sounds being triggered and controlled by someone's brain." (Haill, 2012)

The software used by Lucian Haill uses spectral analysis to extract the energy levels from the different frequency bands. The software uses the different frequency bands to control the synthesis process. Despite the meditative character, her music, seems to possess an odd regularity, which is very similar to the regularity found in pop music when compared to the irregularity and variability of brain signals. This surprising regularity and predictability of the musical output, suggests some deep manipulation of the signal. This aspect raises some questions on how much is real of what's heard and how much is pre-composed and then played live. It is spontaneous to ask what is the sense of deeply manipulating the original signal if the artist has chosen to transfer to the audience a sense of the brain in the first place? Furthermore, it is a well-known fact in cognitive psychology that the human mind cannot consciously follow or control visually or aurally more than five or six objects simultaneously (Alvarez and Franconeri, 2007). Hence Haill's claim of controlling eight independent instruments per brain lobe seems impossible with a conscious intentionality from the performer. It can only happen by patching an unpredictable brain signal to some synthesis parameter, but in such system there is no possibility for control by the performer and no possibility of creating preconceived regular structures. How then can Haill create such repetitive and regular music?

Caludia Robles constructed her own hardware from examples given on the OpenEEG website (OpenEEG, 2012). In her performance, *INside/Out*, she explores

> "the materialization of the performer's thoughts and feelings on the stage. In the performance, imagination becomes spatial. The stage is a place for the appearance of the invisible." (Robels, 2012)

Robles uses recording of audio and video material arranged temporally and spatially by brain activity. It is not clear how these choices are made, and if or how the performer selects the sound and video material. From the description it seems reasonable to think that a sort of spectral analysis is performed on the brain signal, but the connection to the material remains completely obscure for the audience.

In a similar approach, Alex Chechile applies spectral analysis to brain signals to control the sound spatialization (Chechile, 2012b). It seems a better option to use the EEG to control the sound spatialization because it generally requires less parameters than sound synthesis and because previous research showed that the complexity of brain signals can be effectively reduced to consciously control few parameters (Wentrup et al., 2005). Also, the low-frequency oscillatory nature of brain rhythms appears to be a good candidate for the direct mapping to rotating spatialization (it might have been used by the author in one of his performances (Chechile, 2007)). Alex Chechile also created:

> "A system that changes a musical score to reflect the performer's cognitive state while reading the music. In this system, a portion of the score is prewritten, and another portion of the score is blank. By the time the performer gets to the blank portion of the score, the system would fill it with additional music generated by the performer's cognitive state when reading the pre-written section. The generated music is formed from a matrix that links cognitive states to associated musical patterns that were written prior to the performance." (Chechile, 2007, 2012a)

.

The idea of score-generation introduces an extra element in the feedback loop. Every score leaves the player with a degree of personal choice that can influence individual parameters (e.g., dynamics, tempo, timbre) or the material itself (e.g., what notes can be changed or disregarded and which ones are played).

A side from performances, a number of interactive installations using EEG control have been created. In such an installation, a person can experience his or her own internal state, through the control of some external parameters. *"Staalhemel"* by Christoph de Broek (Broek, 2012) is a grid of 10 by 8 steel surfaces suspended on the ceiling and played by percussive metal rods following patterns of an EEG signal. The installation distributes signals from different brain regions to the different metal surfaces. It is appreciable that the artist makes no sensational claim of representing somebody's psychology or spiritual world. Instead, the installation is translating electrical impulses to sound for the scope of sonification or experiencing brain-control. The installation appears as a digital version of Lucier's paradigm. Specifically, the electrical brain activity is directly translated into mechanical action, then sound without the need of any synthesis engine. Broek's website explains in detail how the system handles the mental activity, which again makes use of spectral analysis from beta and alpha brainwaves.

Another installation that seems to be influenced from Lucier's ideas is *White Lives on Speaker* by Yoshimasa Kato and Yuichi Ito. The amplified brain signal is fed directly to a loudspeaker containing a mix of potato starch and water. This liquid substance becomes solid when excited by fast vibrations. It creates interesting morphing shapes when agitated by the brain activity amplified in the loudspeaker. The aim of materializing brainwaves into solid shapes, which can be called brain-sculptures, is maybe the most interesting aspect of the installation. The research is oriented towards a simple sono-visualization maintaining the original brain signal in as pure a form as possible. It still remains unclear what is actually visualized. Is it really some aspect of the brain or maybe the internal chemical properties of the potato starch?

The use of large numbers is often a simple way of extending artistic possibilities: James Fung and Steve Mann of the University of Toronto built an experiential concert involving the audience with EEG and EKG sensors for the generation and control of music (Fung, 2012). The authors intended to explore how technology influences collective experiences and how the mode of interaction between individuals could change when the feedback loops are multiplied. Again, EEG spectral analysis was used here for the creation of harmony content, while the EKG signal served the rhythmic generation (Fung and Mann, 2012). The use of several EEG devices allowed to extend participation, which is an effective way of involving the whole audience simultaneously in the creative process. Ideally anyone could experience his or her brainwave contribution by influencing the performance at any instant. In practice, it was not the case here, as the feedback of the "performers" showed that what they could effectively control remained somewhat obscure. Among a crowd the individual brain control may become even more blurred.

3.3.2 Between Art and Sciences

Scientific studies combining brain research and music generation have attracted the interest of public funds in recent years with several objectives:

- better understanding brain signals through sonification or translation into music
- building new interfaces for parametric control of multimedia (with MIDI, DMX, OSC protocols), or in the medical field, to allow impaired individuals to control mechanical or electronic devices, such as wheelchairs, doors and lighting in smart houses, robots, etc.
- helping individuals with attention deficit during the learning process, sharpening their concentration,
- increasing well-being through relaxation, meditation, and hypnotherapy.

Figure 3.3: *White Lives On Speakers:* setup.

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The availability of funds toward brain research boosted the interest of artists, neuroscientists, and physicians to collaborate and investigate in new directions. This is shown in the increase of literature output in brain sonification or brain computer interfaces in the recent years. These papers are often the result of multidisciplinary research, ranging from neuroscience and medical engineering to music

Figure 3.4: *White Lives On Speakers:* example of potato starch shapes excited by brainwaves.

technology and composition (Arslan et al., 2005). This new research trend allowed music researchers to access medical laboratories with high quality EEG devices offering the possibility of acquiring better information compared to the cheap EEG headsets available on the market that are typically used by independent artists. While the scientific outcomes of these works are publications in prestigious journals (Birbaumer et al., 1999), the artistic outcomes of such research often proposed systems with limited musical interest that seem applicable only in constrained situations with no much freedom or expressivity for the performer.

Eduardo Reck Miranda, who extended the acronym BCI by Vidal (1973) to BCMI, Brain Computer Music Interfaces, has written several papers proposing a methodology to extract meaningful data from the brain signal for the purpose of score generation (Miranda et al., 2008, 2003, 2004; Miranda and Brouse, 2005; Miranda and Boskamp, 2005; Miranda et al., 2008). The system described in the majority of his papers follows one simple design: for every window of the EEG signal, the system checks the power spectrum, and activates one of four generative rules associated to the most prominent EEG rhythm in the signal (alpha, beta, gamma or delta) (Miranda and Brouse, 2005). The system is initialized with a reference tempo that is constantly changed depending on the complexity of the signal, which is estimated using the Hjorth analysis (Hjorth, 1970). A video demonstration of the system shows how the user's concentration can drive the compositional style between Beethoven and Satie (Miranda, 2012) .

Miranda underlined in several papers the fundamental importance that extracting meaningful descriptors from the EEG signal has for the purpose of extending the expressive possibility of the EEG in music improvisation (Miranda et al., 2003; Miranda and Brouse, 2005; Miranda et al., 2008). Still in my opinion it is not clear if his method really represents a step forward in understanding or controlling the brain signal. As the composer writes:

> "Learning to steer the system by means of biofeedback would be possible, but we are still investigating whether this possibility would produce effective control." (Miranda and Brouse, 2005)

And also:

> "If the system detects alpha rhythm in the EEG, then it will generate the musical passages associated with the alpha rhythms." (Miranda and Brouse, 2005)

This statement seems extremely basic to account for the architecture of an expressive system. The simple one-to-one mapping exposed by Mirada does not propose any new solution in the direction of the author's claim for the need of artificial intelligence algorithms.

Finally, the aim of such a system or research is not completely clear. From the systemÕs description, the impossibility of a smooth interpolation between generative rules is quite evident. In the case of transitional mental states, which is very common, the system would produce a set of different score measures, each one in a different style depending on the detected state. Thus creating a juxtaposition of music styles more than an organic music transition. It is unclear what the artistic added value would be from such a system, or in which research field valuable insights or outcomes can be applied.

An interesting contribution of Miranda's research is the use of the Hjorth analysis in an artistic context, which adds a simple, but efficient temporal descriptive tool beyond the typical spectral analysis.

Future studies are still needed to investigate what degree of control Hjorth analysis offers compared to the spectral analysis because Miranda never reported any assessment of his system or an estimation of how "controllable" it is. The lack of evaluation is quite typical in brainwave music literature. Consequently, It is difficult to draw any conclusion or even build on such research without testing. This aspect is crucial especially in the case of EEG systems where failure and difficulties can be hidden in many aspects, such as in the design, in the EEG hardware, in the positioning, or in the external conditions. Knowledge that a system should work because it has been tested can help correct errors, define standard criteria or algorithms, and speed up the progress for the whole research field.

Few papers in the literature report an assessment of usability for the proposed systems, but the results often seem to disagree. This aspect show once more the complexity of this research field. Mealla et al. (2011) presents a multimodal system involving, tactile sensors, EEG, and other physiological sensors for music collaboration. They also present a methodology for assessing participants' performance and motivation during use of the multimodal system. The analysis shows that the combination of implicit, physiology-based interaction and explicit, tangible interaction is feasible for participants collaborating in music composition. The system also preserves balanced distribution of control between collaborators. Unfortunately, these results have limited validity and cannot be generalized to other EEG systems because of the small set of subjects and the particular design of the multimodal system.

Interestingly, Filatriau and Kessous (2008) report completely different results, despite using a similar spectral approach to Mealla. In their research, Filatriau and Kessous build two systems using physiological sensors for audio-visual synthesis. Their approach is somewhat new: it interprets the bands of EEG signals to construct an ongoing spectrogram image, which is then blurred and interpolated across frames. The sound is created from the spectrogram image through subtractive synthesis from pink noise, thus trying to maintain a connection with the original brain signal. The authors aimed to create a strong correlation between the resulting image and sound, assuming this would bring a better understanding of the performance by the audience. Despite this aim the authors find that:

> "The main weakness of this EEG-driven synthesizer was its lack of playability. Indeed, the user was actually not able to consciously influence the resulting image and sound, mainly because data which we interpreted as input parameters to the synthesis modules, such as the spectral content of EEG signals, were hardly controllable by the human subject. This would tend to mean that EEG signals are not suited to drive a digital music instrument, as they do not allow a control of the resulting sound." (Filatriau and Kessous, 2008)

During the summer of 2005 several specialists involved in brain research from different directions, gathered for over four weeks in Belgium for the *eNTERFACE'05 workshop*. The workshopÕs main purpose was analyzing physiological signals, including EEG, to control sound synthesis algorithms in order to build a biologically driven musical instrument (Arslan et al., 2005). Concerning their EEG-driven instrument, Filatriau and Kessous used several signal descriptors to control synthesis, visualization and spatialization, which included spectral analysis, eye blinking, variation in amplitude of the alpha band, asymmetry ratio (which is the difference between left- and right-hemisphere signals), spatial decomposition (for the

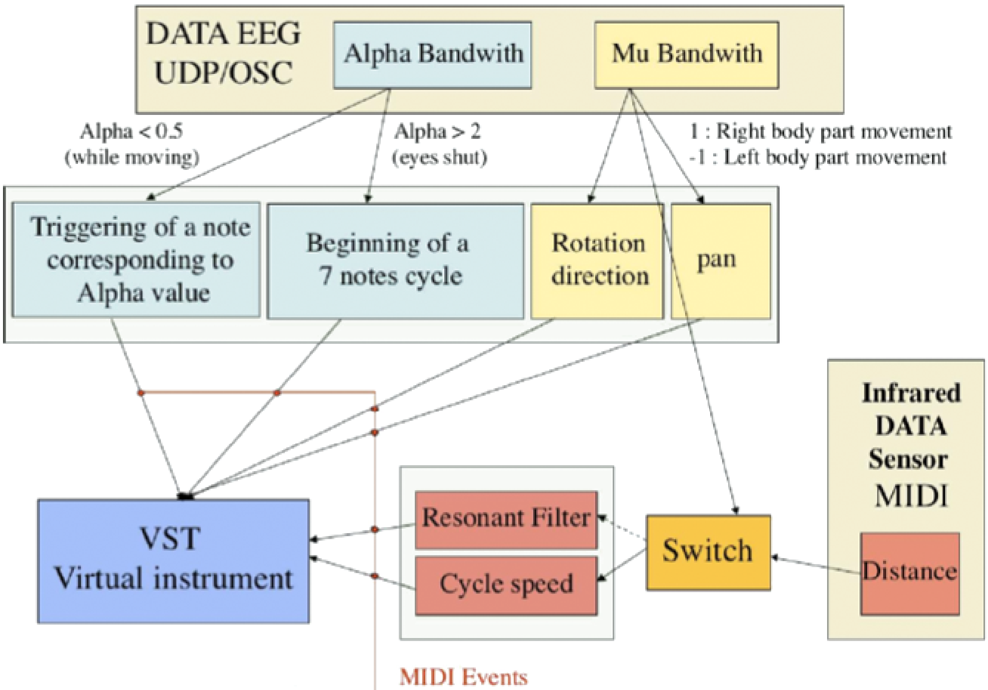

Figure 3.5: Mapping scheme of EEG parameters and sound synthesis for the EEG-driven instrument developed at the eNTERFACE'05 workshop, as reported by Arslan et al. (2005).

classification of brain patterns into categories), and spatial filters (to locate where is the most important electrical activity among the different brain regions). The software architecture used Matlab to extract EEG parameters and covert them to MIDI, then the sound was synthesized using Absynth, a VST-plugin from Native Instruments (NativeInstruments, 2012).

It is difficult to evaluate the proposed instrument architecture without listening to the produced sound or assisting in a live performance. Nevertheless, it is obvious that the authors attempt to first extract as many features as possible from the brain signal (including eye artifacts) to generate enough control parameters to generate sound complexity and provide expressivity. As the authors say:

> "to be interesting from an artistic point of view, a musical instrument must give large-expressive space to the artist; this was a big challenge in our case, and it seems to have been partially effective." (Arslan et al., 2005)

One could extend similar reasoning to the control of song structure, instead of being limited to the direct control of sound parameters.

The use of artifacts to reach a higher degree of control is a controversial question, especially when the claims involve mind control. Every EEG signal contains external spurious influence that are normally involuntary but can be introduced

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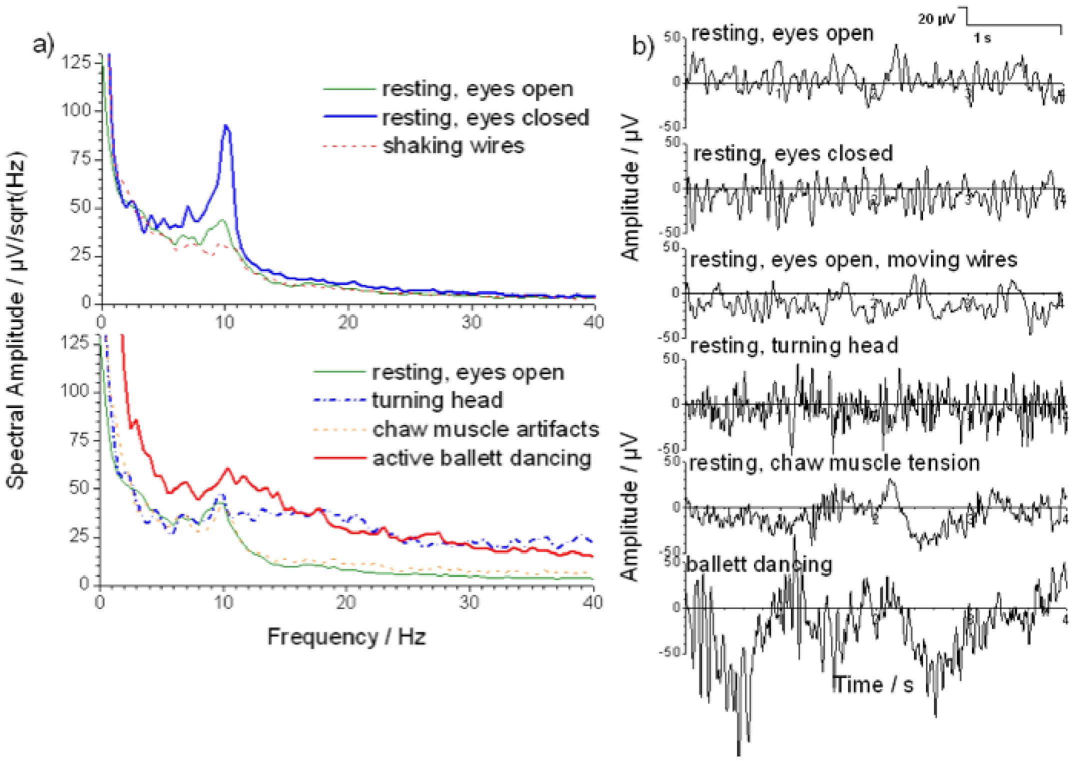

Figure 3.6: Examples of muscle artifacts in EEG waveforms during dance performance. Courtesy of Hinterberger (2007).

voluntarily. A typical example is muscle movements that appear with an amplitude increase in the signal and can be easily detected with an amplitude threshold (Arslan et al., 2005). Hinterberger (2007) reports how artists can make use of the possible artifacts occurring during a dance performance and how to integrate them for the purpose of control. It is an ethical question whether an artist would want to use EEG, suggesting to the audience that some characteristics of the brain are being displayed, and then recur to artifacts to simplify the control problem. Of course it can also depend of how the artifacts are used or in what proportion they are used, whether they are used to control the whole synthesis, or to change a musical scene, or rapidly browse through a set of samples.

A recent research project conducted by Mick Grieson at Goldsmiths University of London, together with the jazz composer Finn Peters, is called *"Behind the Music of the Mind"* (Grieson and Peters, 2011; Grieson and Webb, 2011). Despite Grieson's claim to be able to compose music by interpretation of the mind, his system requires about 10-20 seconds to decipher one note that the experimenter is thinking (Grieson, 2012). It is difficult to think about compositional freedom when the system can only estimate one note at the time from brain signals. It seems quite naive to follow such example, when it is obvious for such simple data control the need for strategies to control higher compositional parameters.

What is also surprising is media sensationalistic claims on the research:

> "Musicians may soon be able to play instruments using just the power of the mind. As is demonstrated in the recent album 'Music of the Mind' of jazz musician Finn Peters." (StudiumGeneraleGroningen, 2012)

These statements are extremely inaccurate and misleading. Artists and scientists often allow the media to blur boundaries of their research making it seem more ground-breaking than what it really is. In an interview, it appeared obvious that Finn Peters listened to the pitch-shifted brain wave signals and transcribed it on paper for a jazz ensemble, after following his subjective perceptual choices (Grieson and Peters, 2011). This is not *"play instruments using just the power of the mind"*. Very often the simple acquisition of brain signals and connection to some musical output is called mind-music, which suggests the possibility of translating thoughts into musical structures. An example of mind music would be a performer controlling winds sections at his will. A more proper terminology, then, would be *"musicalization of electrical brain activity"*, as it shows the limitation of what we can really extract from the sensors.

3.3.3 Scientific research: brain sonification

A more rigorous and systematic research field for the sound synthesis of data is sonification. Several psychoacoustic facts show that translation of data into sound is useful when the data amount is too large or complex to be scrutinized by observation. It is easy to scroll through large amounts of data extremely fast, just by listening, because digitalized audio uses 44100 samples per second with CD quality. The sensitivity of a human ear for the detection of complex sound patterns and loops makes it a perfect tool for the detection of inner structures. The ability of the human auditory system to distinguish between several simultaneous voices or instruments even in a noisy environment (in contrast to the visual system's serial processing of multiple objects), provides a particularly good reason to use advanced sonification. This ability of the human auditory system also extends to its ability to learn to deal with multiparametric data sets, such as EEG. In the case of EEG data, the idea of sonification goes back to 1934 when Adrian And Matthews not only verified the first EEG measurements by Berger but also attempted to sonify the measured brainwave signals in order to listen to them *Berger31, Matthews34*. This was the first example of sonification of brainwaves for human display.

More recently Hinterberger and Baier (2005) proposed one of the first methods for the parametric sonification of the EEG data in real time. Their method takes six frequency bands that are assigned as instruments to a MIDI device. From the slow evolving partials, such as theta and delta (0-7 Hz), rhythm is extracted using a threshold to fire MIDI events when the threshold is crossed. The pitch of each event is calculated from the time difference between successive peaks, while the velocity is a linear scaling of the total amplitude of the power spectrum. Aesthetically dull is the choice of using standard MIDI sound banks for the synthesis of the sound timbre. The reader has to remember that in this field of research, however, the focal aspect is the reliability of parametric mapping and its recognizability. Aesthetics are a secondary priority. The system is evaluated in an experiment by having subjects performing a discrimination task using parametric sonification in real time. The reported results show that self-regulation of the EEG signal is possible using orchestral parametric sonification. This confirms that the multi-parametric representation of amplitude, frequency and rhythm can be successfully exploited for information extraction. The results also present the different regulatory parameters used by different subjects, which further show intrinsic differences of mental processes between individuals.

In a recent article, de Campo et al. (2007) propose and test a new system for the EEG sonification, test it and draw conclusions on possible developments. The system was developed to satisfy the requirements of a medical center which typically uses long-time EEG recording (usually between 12 and 36 hours) and needs real time screening. For the first task de Campo et al. chose to speed up the data reading by sixty times. In doing so, they moved the alpha band (8-12 Hz) to the center of the audible range (480 -960 Hz). The real time sonification uses the separation of the signal in six frequency bands (alpha, beta, gamma, delta, thetaLow, thetaHigh), and the power of each bands modulates the amplitude of an oscillator for the sonification. The carrier frequency is modulated with the band-filtered EEG signal to represent the signal shape detail. A final test evaluated the usability of the system for the medical purposes and the ability of the users to distinguish different diagnostic scenarios just by listening.

3.4 Conclusion

EEG application for music performance started in the mid 60s with research from three authors, each with distinct personal approaches. Alvin Lucier directly connected sub-audible brain signals to loudspeakers to avoid its denaturalization and produce sound through kinetic phenomena. Richard Teitelbaum used EEG signals as voltage control for a synthesizer's parameters, and Rosenboom proposed the idea of investigating and understating features underlying brain signals to achieve a degree of conscious control of musical structure.

From a general overview from the field of brainwave music, it seems that modern artists still encounter difficulties when proposing new paradigms that go beyond the first milestones set by these early pioneers. In particular Teitelbaum's approach is frequently chosen for its immediacy and technological simplicity of realization.

Most artists following this direction make use of cheap headsets available on the market (Emotiv, 2012; Neurosky, 2012; IBVA, 2012). These headsets are delivered with softwares packages able to send control parameters via Open Sound Control. While the delivered software makes it quick and simple for the performer to set up a sound-translating engine, such solutions also creates a platform prone to allowing performers fall into stereotypical performances. It is typical to assist a person sitting alone on a chair wearing an EEG cap seemingly meditating, while hypnotic music flows for the loudspeakers. Such situations make it difficult for the audience to understand or imagine what kind of control the performer exerts on the sound or visuals, hence making artificial the reason for using a device such EEG on stage. This aspect raises several philosophical questions, such as whether the audience should be able to understand what is happening on stage or not, or what the artist is doing? Is it right that certain degree of faith is required from the audience to believe that the performance is really live and not a recording? What happens if then the artist intentionally lies, presenting a recording instead of a performance? What are the requirements when wearing an EEG during a performance to allow the audience understand what is happening? Should the artist involve the public?

The kind of control that is embedded into an instrument is an important part of the artistic product and beauty. Sometimes, it is not important to understand it because its effects are maybe more artistically relevant than what actually happens. Nevertheless, both the generated output and the system construction should have a role in the artist's choice of what to show during the performance. If the control has a large role in its display for the audience and is not made visible, then a large part of the performance also disappears.

Another important aspect concerns the quality of control that the artist has and frequent claims of mind-control that suggest the possibility of shaping sound parameters with clear intentionality. A deeper investigation shows that most artists cannot have conscious control of their material. Instead, it is more a mapping between spontaneous and uncontrollable electrical impulses with music parameters. From a brief observation, it appears evident that most performances use the stream of numbers without questioning its nature. Subsequently, the performer has no control. Instead, he or she acts as an electrical source of unconscious information, uncorrelated to will. Can we do better than this and transfer even-small just a small degree of will into the performer's control data?

As Miranda says

> "On the whole, these systems do a good job of capturing the EEG from the forehead, but they are rather limited when it comes to using the EEG in meaningful ways. The problem is that the raw EEG data is a stream of unsystematic, "random-like" numbers of little musical interest. Sophisticated analysis tools are needed to decipher the complexity

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> of the EEG before any attempt is made to associate it with musical parameters, and this is a very difficult problem. Apart from breaking the EEG signal into different frequency bands, such systems lack the ability to detect useful information in the EEG. Consequently, they are unable to offer generative music strategies that would take advantage of such information." (Miranda et al., 2003)

However, despite the sensationalistic claims of some media, who report that composers able to exert mind-control, the outcome of the scientific research of composers is still very limited and bears little musical interest. Such is the case of Grieson and Webb (2011), where a computer can estimate only one note at a time, or Miranda et al. (2003), where the piano plays musical measures imitating composer's styles following generative rules without much expressivity for the user. Furthermore, reported systems have rarely provided an assessment of their actual usability of control, making it difficult to estimate their validity and reliability.

As is the case sometimes, composer's research is not musically interesting, and pure scientific research, that are not intended for aesthetic results, can produce fascinating sounds. It is the case of auditory display and sonification which is a field of research that expanded in the last several years (Hinterberger and Baier, 2005; de Campo et al., 2007). The proposed systems, are tools for data inspection through sound, but very often create musically interesting "compositions" (Ballora, 2011).

4 General problems of an EEG performance

From a general overview of the brainwave music field we notice that composers often use EEG with the outspoken intention of displaying invisible aspects of the performerÕs mind through the music played to the audience. By the end of the performance, the audience rarely feels that they have witnessed a materialization of the performer's mind. This result is caused by the decision to use the EEG without the awareness of the several contradictions intrinsic to every brainwave performance:

- EEG evokes the magic of telekinetic control, but hides the physical gestures which allowed the audience for centuries to infer the player's intentionality,
- the audience has the expectation of seeing something without knowing what. This expectation is, by its premise, bound to fail and is guaranteed to generate disappointment.
- the performance aims to show thought signals occurring in the brain, but translates its signal after several steps, that involve spectral transformation and synthesis processes. This methodology progressively denaturalizes the signal leaving no connection to the original brain waveform and the initial purpose of the performance,
- the electrical potentials from the scalp that also contain the internal noise of the sensors, are often translated into control data without any modeling or understanding of the nature of brain activity. This provides data, but it is rarely controllable by the performer. Can the display of an uncontrollable signal replace the expected mind control?

The audience cannot understand what the performer is doing, what kind of control is there, and how it is achieved. The mind of the performer remains hidden to the audience, despite the claims of the program notes or the media. In the rest of this chapter, I will analyze each of the previous points to raise awareness about their artistic implications. Last, I will discuss my opinions of what characteristics are required for an EEG system used for creating brainwave music.

4.1 Modality: installation, live, or non-live performance?

The first question one should ask is why do artists want to show the state of a performer's brain to an audience and instead of letting every audience member experience his/her own brain states individually by using EEG installations? Self-perception is the strongest and easiest effect to achieve. An installation overcomes many of the contradictions of a performance. For instance, the brain is visible and perceivable because the person wearing an EEG headset is aware of his or her internal state and can relate it with the specific interactive result. Despite these advantages, an EEG installation does not allow to transfer the experience of mind control to a large audience, letting the public witness the social and technological implications of mind control. What are the risks of using the EEG in a performance? What are the differences of using the brainwaves in real time or not?

In the previous chapter, I described one audio-visual performance that used pre-recorded data (Casalegno, 2012). Observing the video, one feels distant from what the two artists were aiming to provide to their audience. They were unable to give their audience the target experience that was to simplify the brain's complexity through sonification and visualization, probably because what is displayed is a subjective manipulation of an EEG signal.

The historical review made clear the artistic priority of displaying mind control rather than the use of the brain signal in a non-real time performance. The use of EEG in a live performance allows the feedback loop that connects the performer's brain to the EEG signal. The feedback loop connects the EEG signal to the sound production, and the sound to the ears and the brain of the performer. The absence of such loop, as in the case of a recorded tape, leads to the mere presentation of an anonymous signal. Specifically, brain signals aurally or visually translated loses its strong connection to the brain, to the moment, and finally to the audience. The connection is lost because brain signals could have been collected anywhere else, in an undefined past, from an unknown person, or even from a different source. Brain signals converted into visuals and sound does not necessarily simplify the comprehension of the brain, and it might appear even more abstract than the brain itself. The audience that has no idea of how a brainwave might look or sound, cannot relate to the performance beyond enjoying its aesthetics. Furthermore, the aesthetics are disappointing compared to the initial artists' claims.

It is easier for the audience to relate to a live performance with a person on stage producing brainwaves because the principal aspect of EEG in a performance is the telekinetic control and not the brain signal. The audience has some visual reference, that might connect to the produced sounds. For instance, eyes movement of the performer, facial expressions, or closing and opening of the eyes can each produce a different telekinetic control response and hence, produce different sounds. All of these EEG performance elements assume an even stronger theatrical impact on the audience than in a normal performance because of the absence of large gestures.

The only argument that could support the choice of using a pre-recorded brain signal must be connected to some peculiar properties of the signal itself. For instance, whether the EEG signal contains some data structure with special features that makes it unique for sonification. I found no evidence, neither in my research, nor in the literature of peculiar mathematical properties that suggest such insight into the brain signal.

In the case of a live performance, however it is also very difficult to involve the audience. The main problem is how to translate to the audience the performer's telekinetic experience which is by its definition invisible. As much as brain control is such an extraordinary and empowering experience for the performer, it is just as much a frustration for the observer who cannot directly feel the performerÕs experience. It is easy to imagine for example how controlling the pitch of a sinusoid with the mind can be an ecstatic telekinetic experience for the performer, as much as one of the most boring examples of computer music for somebody listening. During a performance only the performer wearing the EEG can be aware of his internal state and feel the emotion of brain control directly. The experience can be transferred only if the audience is able to infer, from some detail, the internal state of the performer, and then relates the representation of the internal state with what the performer is telekinetically controlling.

It is arguable that it is not important for the audience to understand the technology and methodologies for a performance to be interesting. Instead, the purpose of a brainwave performance is very often based on the methodology itself, which is the display of brain control and its use to translate the invisible into visible. It would be like attending a dance performance in which the dance happens behind curtains, or going to a concert and surprisingly assist to Cages' *4.33'*. Such performances make sense when proposed for the first time because of their extreme concept, but do not need to be reinterpreted by different artists. Modern brain music performances seem a digital reproduction of Teitelbaum's pieces with some variations such as the presence of visuals, or sound spatialization (Robels, 2012; Haill, 2012). As part of the audience I found these performances quite frustrating because they claim to visualize some aspect of the brain of the performer, but do not provide any possible insight.

The most important requisite for such performances is the audienceÕs trust that what is happening is really controlled by the brain. This is because without any brain insight there is also no verifiability of what's happening. The program notes and media claims are important to create a favorable mindset in the audience. Haill for example claims that her performance *"evokes a mysterious atmosphere when you first hear sounds being triggered and controlled by someone's brain"* (Haill, 2012). This statement seems quite misleading because it is obvious that the perceptual properties of the sound are related to the music material and the synthesis algorithm used. Consequently, the audience does not directly listen to the original brain signal. What creates the atmosphere of mystery is probably the theatricality of the presentation, through a state of self-illusion in the audience. The audience believes that the music comes from the brain, which then creates wondrous expectations about whether the music would actually be controlled from the brain or not.

A degree of wonder is present in every good performance, such that an able performer might be thought of as a magician who knows how to raise expectation in an audience and then satisfies it at the right moment. Modern performances of brainwave music fail to take this into account because they generate sound while the mind control is still invisible to the audience. As Schloss says:

> "Magic in the performance is good. Too much magic is fatal! (Boring)." (Schloss, 2002)

The amount of magic must be somewhat balanced with the amount of belief required by the audience. It is a delicate balance, just as in a good magic show between what is promised, what is hidden and what appears. The trick must be visible to show there is magic: without visible mind control the telekinetic magic remains hidden behind doubts. How can we expose such control?

4.1.1 Technical tools

Despite the lack of a clear evaluation of how reliable brain control can be, particularly in the experimental music field, BCI literature reports many articles that seem to suggest the possibility to have EEG control on simple actions. Birbaumer et al. (1999) have shown that humans can self regulate their encephalogram as a channel for information transfer out of the brain. In particular, slow cortical potentials can be self regulated (Hinterberger, 2007). This thesis is based on the assumption that we can self-regulated our brain consciously to obtain some degree of control, and will confirm this assumption with a simple methodology exposed in the next chapter.

4.2 Spectral analysis

From an overview of what is currently the the state-of-the-art of in brainwave music, we observe that most EEG-based performances approach the problem of mind control with the use of spectral analysis (Haill, 2012; Robels, 2012; Chechile, 2012b). EEG-based performances sometimes seem to be a stereotycal and quick choice, perhaps taken without an awareness of the limitations of spectral methodology or considering the advantages of other techniques. It is a quite common and intuitive choice for the composer to connect the fluctuating spectral values to the parameters of a virtual instrument and rapidly obtain a sound result. To achieve brain-control with such an approach requires the possibility for the user to voluntarily change the spectral content of his or her brainwaves.

It is my belief that spectral content belongs to a more abstract cognitive category for out perception of the world compared to temporal content as spectral features of a bio-signal might be less intuitive to control rather than time features: they might be hard to perceive internally or to visualize for control. This further complexity may introduce a delay in the resulting sound effect which inform the performer of his/her actions, making the EEG-learning phase more difficult. Furthermore, spectral analysis cannot separate the relevant information in brain signals from the noise introduced by the EEG sensor. Some control signal is present even when the EEG is not on the head of the performer.

Artists who are more interested in obtaining some quick sound over attempting to really understand some aspect of the brain, approach the brain, the EEG and the analysis techniques as a black box. They patch EEG signals to obtain a sound, even if it might be scarcely correlated to the original brain signal. As a result, we appear to be content to translate the brain without understanding what language it speaks. We seem to use the EEG as a data source, without understanding connection with the performer's intentionality. What is achieved is a kind of unconscious influence on the music but can we call this mind control?

4.2.1 Machine learning techniques

Statistical methodologies can be used to train a system to recognize particular patterns in the temporal dimension of a signal appearing in connection to specific ideas or imaginative tasks for classification purposes. Several papers in the field of BCI have shown the advantage of replacing the simple spectral analysis with more advanced statistical tools, such as independent component analysis, singular value decomposition, and principal component analysis for the implementation of machine learning techniques and classification algorithms (Kubler and Muller, 2007). In particular, Wentrup et al. (2005) have shown that machine learning algorithms for classification together with source localization procedures could allow the classification for a multitude of conditions. For source localization, the authors detect potentials on the brain scalp while the user imagines movements of the right and left index finger. The ability to extract precise patterns appears to be a more robust way to reach conscious control as they are connected to precise thoughts. This is in contrast to creating a vague internal state normally used for

Spectral Analysis, in which it seems the brain is rather used as an uncontrollable source of data (Arslan et al., 2005).

4.3 Theatrical consequences: the dematerialization of gestures

An artistic performance might be considered a materialization of the artist's will and poetic ideas through stage representation. The EEG allows the opposite: such that the performer's control becomes immaterial by passing through an invisible signal. The invisibility of the performer's gesture breaks the possibility for the audience to establish a cause-effect relationship between will and result, between ideas and materiality. It completely alters the way a contemporary performance should be thought and the relationship between the performer and the audience (Schloss, 2002).

This problem is related to modern technologies of audio recording and reproduction, which brought the possibility to reproduce sounds that existed in the past and to make them present again. The combination of such techniques made it possible to play a recording and trick the audience to think that the sound is effectively produced live on stage by a particular object. Especially when the object on stage is a new instrument with unknown timbre or physical properties. This possibility turns now against the computer musician when he or she is producing live music, meaning that the audience is unable to imagine what kind of control and processes are happening on the other side of the screen. As a result, we can no longer understand the performance from a physical point of view. Is it really happening live or not [1]? When using EEG, the problem becomes even more dramatic because the performer often does not move at all and operates no control interface. So it is impossible to understand what he or she is really doing.

Beside the recording techniques, the loss of causal-effect relationship is also connected to the way gestural interaction changed with the introduction of electronic instruments. For more than thirty-thousand years, humanity experienced a one-to-one relationship between gesture and produced sound. In last thirty years, the possibility of more complex control strategies has broken this one-to-one relationship resulting in the disconnection between sound and its source, its effort. Cadoz (1988) defined the term *instrumental gesture* to describe the physical interactions

[1] The definition of *'live music'* has consequently been broadened. It can range from playing a song composed by another artist from a playlist to controlling all aspects of a composition until the micro level of samples. The use of the term "live" has broadened to cover a large variety of artistic scenarios, like: the performer is on stage, he or she is filmed through a webcam from another location, his or her robots are on stage performing an improvisation (Auslander, 2008).

between instrument and player. The instrumental gesture has to satisfy three requirements: it contains information conveyed to the audience (*semiotic*), the actions of the performer on the physical system (*ergotic*) and there is a reaction from the instrument towards the performer (*epystemic*). An electronic system typically breaks or challenges at least one of these requirements by interrupting the physical flow that allow the cause-effect relationship between gesture and sound (Cadoz and Wanderley, 2000). In the case of the EEG, interruption of the cause-effect relationship goes even further because the gesture disappears completely. Consequently, this begs the question: do we need then a more complex definition of gesture?

We can compare the two instrumental chains describing a normal digital controller and the EEG. In the first case, the controller receives the motor input from the user. The gesture is processed by sensors and transformed into input variables in the controller, and then sent to an algorithm that performs the synthesis. The loop is closed when the performer perceives the result of his action and makes a new decision. In the case of an EEG motor program, gesture interpretation sensors and the controller are part of the same unit. There is nothing moving, and the intentionality of the performer is freed from the need of the smallest physical action. The complete absence of gesture in EEG expands the distance that a normal digital controller already brings between audience and performer (Arslan et al., 2005).

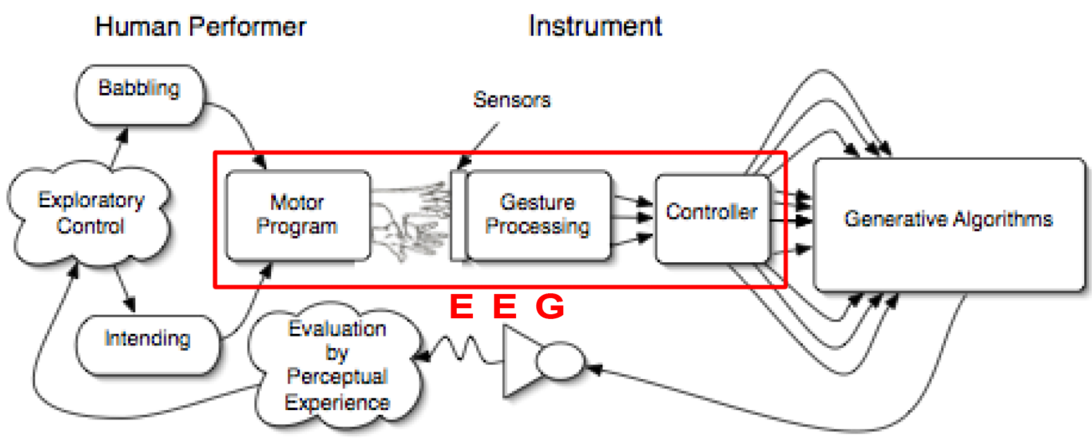

Figure 4.1: Diagram of a normal electronic instrumental chain, in red the EEG device embedding motor program, gesture processing and controller. Courtesy of Wessel (2006).

Computers inspired complex possibilities of mapping human gesture to sound. Computers allow sound production in the absence of gesture, or gestures in absence of sound. This aspect creates as many new possibilities for the performer as much confusion for the audience or difficulty to relate to the performance. In the case of a physical controller connected to the computer in a customized way, the problem of gesture depends on the focus that the whole performance has on the interface and on the artist's use of it. The performer can use the controller as a tool to help the improvisation, so that the controller becomes a sort of intelligent system that reduces the physical and intellectual workload on the performer. As a result, the performer can concentrate on higher structural controls. In this case, the audience' lack of understanding could be justified by the (new) sonic possibilities that the system generates.

It is different when the controller is the protagonist of the performance as in the case of the EEG: its metaphorical and evocative power is so dense of expectation from the audience that cannot be considered as a mere controller that can be introduced without preparation. Mind control is the main thematic of the performative act and is almost imposed by the tool itself. The artist cannot avoid finding a way to allow the audience understand at least a part of what is happening. This is complicated by the very nature of the EEG: it offers the advantage and disadvantage of having no gestural control.

4.4 Visualization of the brain control

To connect the audience to the performance, the performer needs a way of transferring some gestural information back to the audience. In a paradoxical way, the EEG allows the dematerialization of the gesture, but the artist has to render the control visible again by recreating gestural information to let the audience understand what is happening and experience telekinetic control. Considering our visual-oriented society one possibility would be a visual legend for the audience:

> "A visual component is essential to the audience such that there is a visual display of input parameters/gesture" (Schloss, 2002).

It is possible, though, that such a display would become too didactic and cumbersome to understand and follow, discouraging and distracting the less scientifically-oriented audience.

One rather common aspect of most EEG performances is the immobility of the performer maybe to avoid the presence of artifacts, or maybe to reach a deeper (somehow doubtful) meditation. Nonetheless, movement is one of the dimensions that can bring variation and interest. The visible effort often enhances the performance and helps visualizing intentions. Moreso, even further on this direction the performer can sometimes use his or her gestures in a creative way to introduce musical changes or to trigger events.

Another possibility would be to have the performer accomplish particular physical tasks that connect to specific mental states that are predictable by the audience. Personal experiments (and simple common sense) show that brain outputs completely different signals in deep sleep versus solving a problem of algebra. These or others actions may be used to create different situations that the audience can predict from self experience and expect different musical results. In the next chapter, I will explain a personal approach to visualization of the brain signal.

4.5 Consequences on the conception of an EEG performative system

4.5.1 Mapping strategies

The simultaneous presence of large amounts of incoming EEG data and the necessity to output several data streams to have sufficient expressivity in sound generation is one of the biggest problems in designing an instrument for EEG music. It is the creative task of the composer to carefully design the instrument that allows the mapping of these two complex data sets. The EEG-brain system produces several channels of rather noisy data with sample rate of 128 Hz or 256 Hz. As we saw, using methods of machine learning and pattern classification, this quite large data stream can be used to reliably classify and recognize at most two or three scenarios. In turn this allows the allowing conscious mind control for the same number of variables (Wentrup et al., 2005). The problem seems even more complex considering that these scenarios cannot be controlled simultaneously because system parameters must be addressed one at a time. This problem derives from the intrinsic nature of classification. The software cannot extract a representation of an intermediate category made of the simultaneous presence of two or more states. For example, if one item is a tiger and the next is a pair of scissors, what is the intermediate category? Should the software produce an intermediate state with mixed characteristics or a third object? Finally it is doubtful whether the performer can think about two different items simultaneously to control two variables.

At first, it is very important to decide the best mapping strategy for the sensorÕs output to the inputs of the synthesis engine because of the reduced number of controllable variables. As Chadabe (2002) says:

> "The fewer the number of variables, the more powerful is each variable: changing one of two variables for example is changing half of the system." (Chadabe, 2002)

Unfortunately, it is common experience that the lesser the variable, the more difficult it is to achieve sound complexity and structural variation. It is important to reach an optimal balance between reliability of the system for direct control and indeterminacy to allow surprises and variations.

Rovan et al. (1997) categorize the mapping strategies into three categories: *one-to-one mapping*, where one parameter is connected to one gesture; *divergent mapping*, where one parameter controls several synthesis parameters; and *convergent mapping*, where several parameters control few synthesis parameters. One to one mapping may not be the most appropriate for the EEG, because it does not take opportunistic advantage of signal models for higher level couplings between control gestures. Divergent mapping, however does not allow access to the low level micro features of the sound waveform. Finally, convergent mapping is harder to master but proves to be the most expressive of the three because it accesses structural control from the signal sample level (Rovan et al., 1997).

It is difficult to choose the appropriate mapping strategy because of the characteristic complexity of the EEG signal. The scarcity of control parameters using pattern recognition suggests that one should use to use EEG with some sort of divergent mapping. Structural control would be possible in such a system but brain signals would disappear, making the mind even more immaterial and invisible for the audience. Translating the noisy signal at the signal level would allow the direct display of the mind and its thought processes, but that would lose the musical possibilities and would probably result in a hectic solo performance of a jittery signals with limited controllability and sonic expressivity.

Several artists propose mapping strategies to control their system using very few parameters for intuitive live improvisations. For instance, Angel Faraldo built a system in which eight faders control the synthesis at micro, meso and macro levels. These levels respectively represent the waveform samples, phrases, and sections in the structure. The interesting aspect of Faraldo's architecture is the possibility to simultaneously have convergent mapping, to compose the waveform precisely at the micro level, and divergent mapping, with several parameters controlling higher level envelopes affecting the structural evolution (Faraldo, 2009). Jan Trutzschler von Falkenstein, uses a Manta touch sensitive control to interpolate between Self-Organized Maps of preset sounds (Snyderphonics, 2012; von Falkenstein, 2011a,b). Using touch sensitive buttons, the Manta can be thought of as a three-dimensional controller where *x-y position* identifies the button and the *z-axis* is the depth of touch. Younes Riad uses two joysticks to control several parameters of different software samplers. The samplers are programmed in such a way that parameters are dynamically assigned depending on the sampling algorithm chosen. Dynamic mapping allows the use of fewer parameters but requires the user to know which synthesis engine he is using at any time and which parameters are controlled by the joystick (Riad, 2012). The next chapter of this thesis will report a specific approach to solve such mapping difficulties.

4.5.2 Instability

When designing his or her system the composer must consider the noise introduced by the EEG sensors. The accuracy of the EEG sensors is usually very low, especially with the cheap new generation of commercial headsets. An additional problem is caused by the different conditions of training between rehearsal and on stage. On stage, the brain signal might change because of external reasons such as lights, humidity, etc. It is the important to retrain the system before the performance. Furthermore, during the performance the performer needs a certain degree of attention. There is an intrinsic conflict in the idea of relaxing while concentrating, which adds a second level of distraction and indeterminacy in the system. His or her internal tension may change brain signals that do not match with the rehearsal training. This is not a necessarily negative factor if the composer is aware of these limitations and considers them as part of the performance, adding a level of unpredictability, and variation.

A possible solution is architecture able to handle bipolarity from the EEG signal. A somewhat reliable output that flows in connection with global parameters from an EEG uninfluenced by the small errors or deviations. And part that underlies the instability and fluctuations of the EEG.

4.5.3 Thematics

Finally, it is important to think of the possible themes that such a system could address without making use of EEG as a technological gadget that has no real or necessary presence on stage. So far, artists have used EEG to represent internal human states. EEG is a kind of microscope for the internal biological processes such as dreams, cerebral states, anxiety, and concentration. Would it be possible to extend these categories to let the EEG support a broader set of themes?

4.6 Conclusion

In this chapters I exposed possible consequences and risks of using EEG for artistic productions. One of the major contradictions of brain art is the intention to show mind control. The audience has an expectation to grasp some aspect of brain activity, but the artist typically presents a subjective transcoding of the electrical brain signal into sound or visuals that reveals nothing of the mind. The artistÕs subjective presentation of the brain signal then leaves the audience an unsatisfactory experience. Very often this seems the consequence of the fast prototyping of performances based on stereotyped aesthetics influenced by Teitelbaum's initial experiments. Three aspects must be carefully ad critically analyzed to decide what sense has the EEG on stage for a particular performance: technical analysis of the signal, theatrical implications and modality.

Using EEG as a tool to capture data from the brain without questioning the nature of such data, makes it possible to obtain a system that can control some music parameters but often without a conscious control by the performer. The problem is then what do we really want to represent of the brain? Do we want to represent the brainÕs noisiness, or is it more accurate to say we arere representing noise from cheap EEG sensors? The artist can easily patch the signal to control some synthesis algorithms but would that support the claim of mind control that the audience often expects?

Mind control requires an understanding of at least simple data structures in the EEG signal, so that the performer can exert conscious, (mostly) reliable and deterministic influence on the EEG sensors. Modern spectral analysis techniques often used by artists seem to provide a rather blurry and indirect understanding of the signal.

In contrast, techniques of machine learning for classification proposed by many BCI articles, seem promising for the extraction and recognition of few patterns from brain signals. These techniques then discern between the background noise and the relevant information in the data. Thus, they represent a good candidate to provide more extended control than what is typically achieved with spectral analysis.

Every object under the stage lights is covered by the magic spell of the performance; it assumes a metaphoric meaning in the narrative of the actions; a dramaturgical sense arise with theatrical implications. These considerations are complicated by the complete dematerialization of the performer's gesture when using the EEG that determines a lack of the causal effect relationship between action and music result. In this sense EEG is an exemplifies the problem of connecting gestures between modern electronic sensors and controller. EEG on stage brings expectations and questions that cannot be answered by the invisibility of its control signal. When using the EEG, the composer must be aware of the intrinsic tension created by these opposite concepts to conceive a clear performance.

We proposed possible ways of visualizing some aspects of the performer's thought to allow the audience to infer the mind control and characteristics of an optimal system for brain music. Such a system must use mapping in an economic and versatile way to allow only a few controllable parameters to handle aspects of a whole composition, achieving both reliability and expressivity.

The balance between theatricality and technology must be carefully handled such that when the control is not completely understandable, the theatrical setup must support the use of EEG. When the latter is lacking, then the EEG control must be more evident with attention to avoid turning the artistic act into a scientific demonstration. The analytical tools that may allow a more reliable brain control, are not sufficient to artistically justify the use of EEG for artistic performance.

This thesis uses a simple example of machine learning techniques and proves the possibility to extract three patterns from the brain signal to consciously control three variables non-simultaneously using the brain. The system addresses both structural and sample level control to obtain variation and stability. These strategies are embedded in a performance metaphor that addresses the theme of postmodernism via a scan of a performer's internal state when immersed in several challenging situations of our daily lives, as described in the next chapter.

5 A Personal Approach: *'Fragmentation'*

Up to this point, I have presented an analysis of the historical and present context of the field of brainwave music and exposed the theatrical and technical implication of the use of the EEG for a live performance. In this chapter, I introduce my personal approach to the problem of externalizing some internal brain processes in an artistic metaphor to an audience. The methodology described herein has been used to construct the piece "*Fragmentation*", which is an analysis on the internal states of the modern man subjected to stressful situations and massive data streams. The performer's brainwave signals throughout the piece control in various degrees the music structure and sound synthesis in various degrees, thanks to the techniques of machine learning and pattern recognition. I also add some general information for anybody who may start exploring the field of brainwave music for the first time.

5.1 Choice of Hardware

The choice of hardware is the first problem for the detection of brainwaves. There is no widespread experience of EEG sensors and it's rather difficult to access one. Medical EEG machines are useful to familiarize with the type of problems, handling, and limitations, but are completely different to the cheap EEG devices on the market, especially when considering signal quality. The most important requisite is the possibility to record an actual brain signal and it is difficult to verify the signal nature before personally testing the hardware. This situation is further complicated by the need of lengthy training with the controller to get familiar with the feedback technique. In principle, a few days of tryouts are required to test each individual piece of hardware.

There are several cheap EEG devices on the market, for example: Neurosky, Emotiv, IBVA, and OpenEEG prototypes, that can be autonomously built with differing degrees of difficulty (Neurosky, 2012; IBVA, 2012; Emotiv, 2012; OpenEEG, 2012). These products also differentiate in the number of sensors, sampling frequency, costs, provided softer for interfacing, etc. It is intuitively better to have a high number of sensors because the EEG device must be able to detect brain activity from a priori unpredictable locations on the scalp. In case of few sensors it is advisable to place them in positions where the desired signals are typically present (e.g., occipital hemisphere for alpha waves. It is also important whether the sensors have dry or wet contact since it can be tiring to wet the sensors continuously, and it would make it difficult to use wet EEG sensors during long performances: if one sensor becomes dry, the contact is lost, and the EEG would capture only noise. Sampling frequency is another important aspect because it determines the temporal and spectral resolution of the signal. Finally, it is safer to avoid the direct contact between the brain and the high voltage of the power supply, through the use bluetooth or other wireless technology. Such connectivity would also provide users with a broader range of motion compared to the wired EEG, which can be important for dance performances, for example.

For the research presented in this thesis I used an EMOTIV Epoc headset. It has several good features, like: its 14 sensors offer optimal positioning for accurate spatial resolution; the plastic skeleton of the headset connects the sensors in a rather rigid way to limit mobility within and across sessions to achieve more consistent measurements; the sample frequency of 128 Hz captures a signal bandwidth from 0 to 64 Hz, which is enough to record most of the electrical brain activity. The headset also has a wireless connection and USB dongle to avoid direct electrical contact with the brain and several meter of free movement. A lithium battery provides several hours of continuous use, more than what is needed for a typical performance.

The limitations of this hardware include: the need to keep its sensors hydrated (normally done using standard contact lens solution); the degradation of the sensor pads with time; and the extension of the wireless connection, which is reduced in the presence of heavy electrical and magnetic interference from computers or loudspeakers. In these cases, the usb dongle breaks the connection, which cannot be restored until the dongle comes close to the headset again. This problem can be easily overcome by adopting a USB extension cable.

There are also few bonuses that come with the headset: a gyroscope that generates positional information for cursor and camera controls depending on the head orientation and software for OSC interfacing in Max/MSP; detection of facial expressions from muscle artifacts; estimation of cognitive functions and emotions. This software appears often imprecise in the detection of facial expressions, it has unclear estimation when detecting emotions, and its code or intrinsic statistical strategies are unrevealed because of its company's commercial purposes. It can be used to map synthesis engine to some arcane values, but in general it seems uninteresting and impractical for a performance that aims at some reliable control or to extract significant brain information. The most important limitation is the price of the hardware. While the hardware is delivered for less than 300 dollars, the possibility to access the raw EEG data costs 2000 dollars extra. This thesis used a method to obtain the dongle encryption key that accesses the raw sensor data present in the transmitted signal.

5.2 Software development

All software used in this thesis was written in Supercollider because of its reliable timing in transmitting EEG samples through OSC, CPU efficiency and the ease to implement DSP analytical tools with sample rates different from audio and control rates, such as the ones in the EEG (Supercollider, 2012). From the beginning, I have been inspired by the ideas proposed by Rosenboom. For this reason, I have decided to use pattern recognition to eliminate the noise sources in the signal and allow a reliable identification of a few situations that could be connected to specific actions in the software.

5.2.1 Temporal domain analysis

I used cross-correlation to compare how much the incoming signal matches a set of stored patterns in the system. Cross-correlation is a measure of similarity of two waveforms as a function of a time lag applied to one of them. It is commonly used for searching a long-duration signal for a shorter, known feature. Cross-correlation is similar in nature to the convolution of two functions. Considering two waveforms f and g, where f is the short stored pattern and g is a longer signal representing the real time samples of EEG, the cross-correlation at the sample n would be:

$$(f \star g)[n] = \sum_{m=-\infty}^{\infty} f^*[m]g[n+m] \tag{5.1}$$

where n and m are sample positions and f^* is the complex conjugate of f. The formula essentially slides the f function along the time-axis, calculating the integral of the product of the two functions at each position. The cross-correlation value lies between -1 and 1, with 1 representing perfect match, -1 representing inverse match (which also is strong evidence of correlation), and 0 representing total non-correlation. This is because when peaks (positive areas) are aligned, they make a large contribution to the integral. Similarly, when troughs (negative areas) align, they also make a positive contribution to the integral because the product of two negative numbers is positive. In a typical optimization problem such as function alignment, when the functions match, the value of $(f \star g)$ is maximized. In this case an absolute estimation of how well the functions superimpose is sufficient to provide a value between 0 and 1, which can be easily mapped to whatever software parameter.

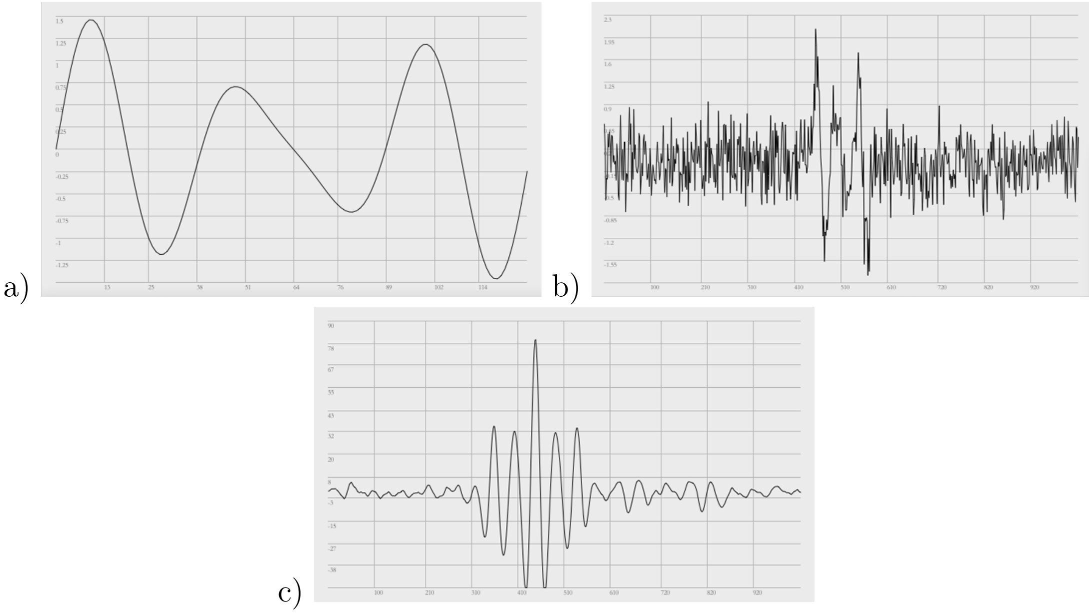

Figure 5.1: Examples of cross-correlation, where the $x-axis$ represents time in samples and the $y-axis$ amplitude in arbitrary units: a) example of the wanted pattern signal, b) example of a similar pattern immersed in a noisy signal, c) cross-correlation of the two signals. The reader can observe a peak in the center determining the position of max correlation and detection of signal b).

In the case of indefinitely long signals such as with an EEG performance, the f signal is windowed to a specific time duration to allow real time computation. Different tests showed that six seconds were an optimal windowing length for signal analysis, while individual stored patterns had the length of one to two seconds. Another complication with EEG signals is the presence of 14 channels of output occurring simultaneously. Two implementations are possible: *additive*, where the contributions of all channels are added and compared to the pattern relying on the cancellation of an individual difference in the addition; and *global*, where the cross-correlation is estimated and the individual cross-correlation coefficients are averaged to estimate the final matching result. Testing the reliability of the two approaches showed no significant difference on performance.

5.2.2 Pattern extraction

The second important step of pattern recognition is the extraction of reliable patterns for matching. Patterns are calculated by asking the performer to concentrate on specific thoughts, while recording EEG inputs. From a spectral analysis of the signal, onsets are detected to isolate relevant parts. When doing this, we find that noise is, by definition, uncorrelated and the signal is not, and so adding several of these parts creates destructive interference of the noise and strengthening of the relevant parts, thereby letting the relevant signal emerge.

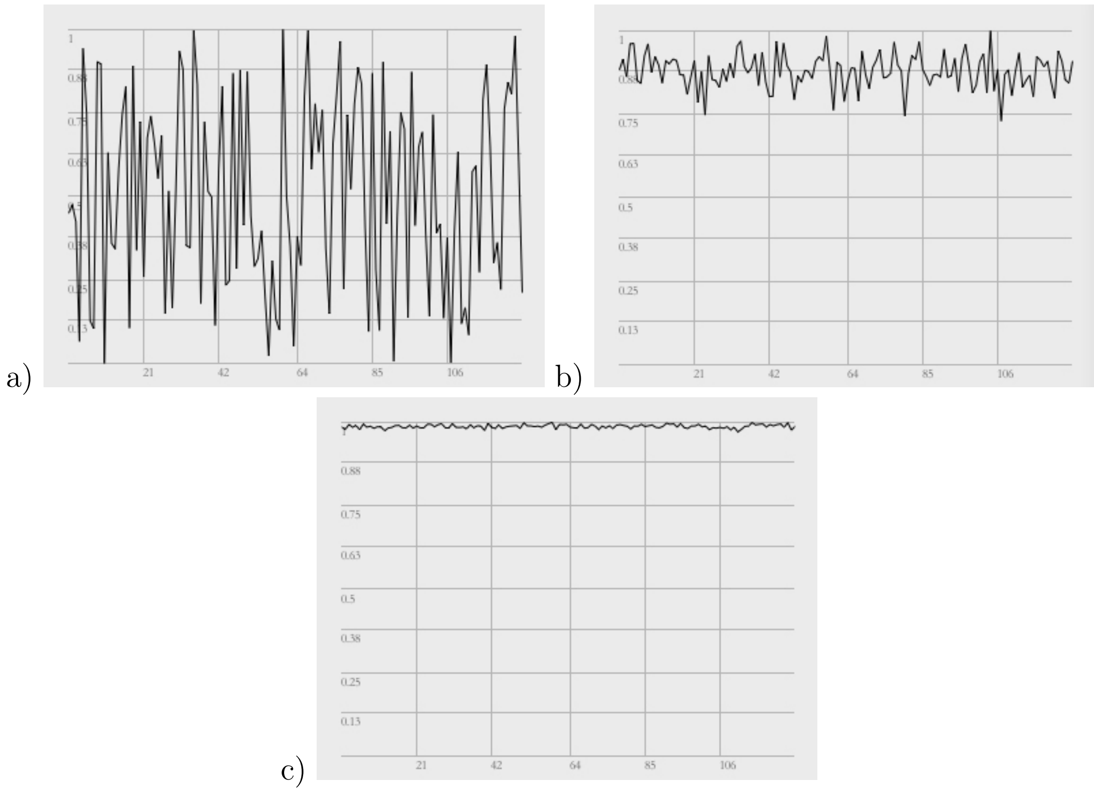

Figure 5.2: Examples of noise cancellation adding respectively a) 1 noise vectors, b) 100 noise vectors, c) 10,000 noise vectors. The uncorrelated nature of the noise determines its cancellation with a sufficient number of additions

The tuning of the technique involves the definition of the appropriate windowing length and the definition of time locking functions to detect signal onsets. This was done using spectral features to extract relevant variations in the signal start and end. A sliding time window of 1 to 2 seconds was found to be optimal for such a task.

Early tests showed the presence of different patterns in the signal depending on different external conditions, such as light intensity on the room and EEG positioning on the head, and not to the internal stimulus (i.e., the thoughts of the user). This aspect suggested the possibility of adopting user training to obtain a flexible system for pattern recognition that could be rapidly re-calibrated. The training is more reliable the more times it is performed provided that the external conditions do not change. In the case of a live performance a training of three to four times has proven successful.

5.2.3 Spectral domain analysis

I implemented a similar approach to the the temporal domain analysis in the spectral domain. In this case, the data that had to be matched was the signal

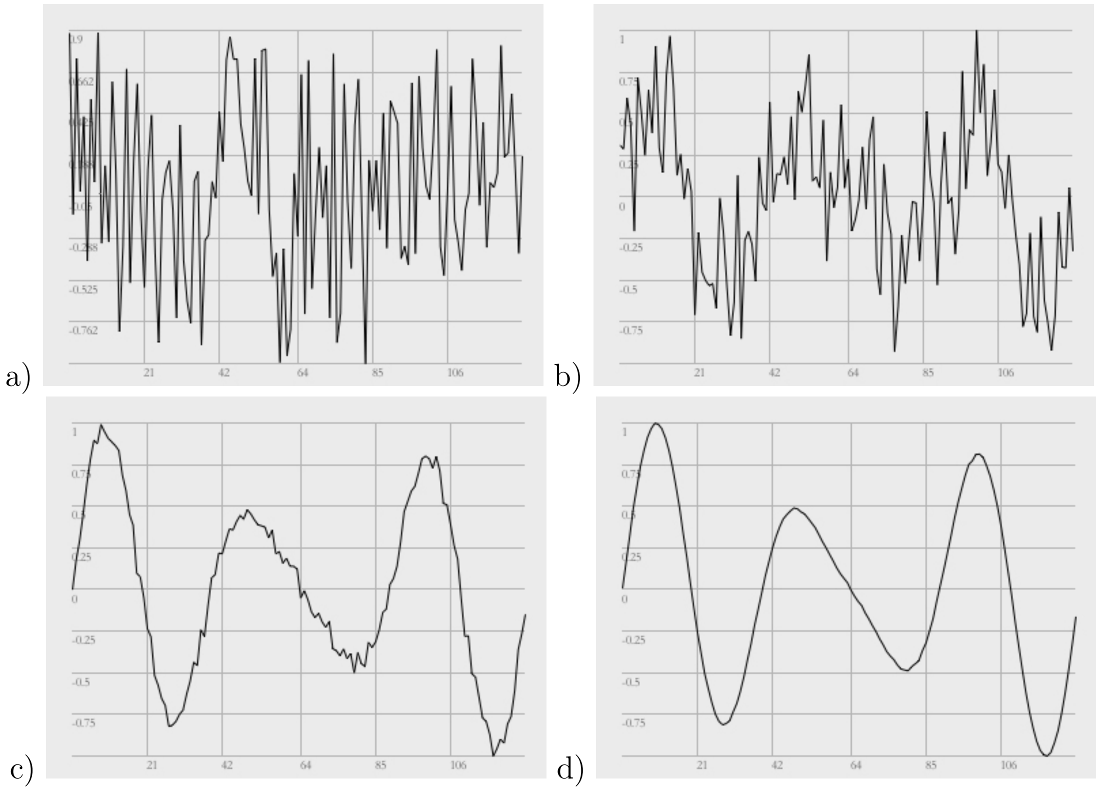

Figure 5.3: Examples of a steady signal progressively emerging from randomly generated noise using a) signal + 1 noise addition, b) signal + 10 noise additions, c) signal + 100 noise additions, d) signal + 1,000 noise additions. The different nature of signal (correlated) and noise (non-correlated) determines the noise cancellation while the signal remains.

spectral envelope. The system extracts patterns by averaging spectral envelopes in the training period and comparing them with the spectral envelope of the incoming signal. Depending on similarity, calculated using cross-correlation, special envelopes are recognized and classified to specific brain states. As in the temporal domain case, this procedure has proven to be robust to some degree of noisiness.

5.3 A practical application: "Fragmentation"

These analytical tools are used in my composition *"Fragmentation"*, which is a theatrical piece exploring the fragmentation of modern man subjected to overwhelming sensorial load and chaotic data streams, from media, interactive connecting devices and hectic social environments. The performer, representing the modern man is required to accomplish different common modern actions while the EEG records his mental activity and provides the source for the sound and visual synthesis. The EEG device is used as a microscope to expose the brain state of a typical modern man in different daily but extreme situations.

The first part of the performance begins with the performer's brainwaves generating music from a phase of deep sleep [1], then from solving a concentration task, and finally from jogging. These are three different scenarios that create three different spectral envelopes connected to specific synthesis algorithms. This performance differs from the usual EEG performance in which the performer tries to internally change his or her brain state to create several sounds. Instead, I attempt to change the performer's brain state from the outside by exposing the performer to different challenging situations. In this way it becomes also possible for the audience to imagine some characteristics of the performer's brain state (e.g., anxiety, relaxation, concentration), or the changes introduced when shifting actions.

For this part of the performance, I used the pattern recognition on the spectral envelope. The different actions of the performer insure reaching completely different spectral envelopes, which are easily distinguishable by the system. The recognition of a specific pattern triggers pre-defined synthesis algorithms that have inbuilt stochastic variation to keep the audience interested. The same synthesis algorithm and stochastic parameters play for as long as the spectral envelope is recognized as belonging to the same pattern. The detection of a new pattern determines the loading of new synthesis algorithms that create a different sonic atmosphere. The incoming EEG spectra are averaged over large temporal windows, which are 10 to 20 seconds long to reduce fluctuations due to internal noise and allow smooth transitions between the three parts. The performer also has a limited control inside each section. Variations are introduced by the general amount of signal amplitude, and influence different sound parameters varying dynamically throughout structure of the piece. In this way the performer can create more or less brain activity to trigger variation in the density, pitch tendency masks of the generative processes, spatialization, or other macro levels.

In the second part the performer, a Butoh[2] dancer, with his brain activity controls the position of an avatar in a three-dimensional virtual maze and has to bring it from the start to the exit while dancing. Depending on the avatar's position in the maze, sound and visual scenes are triggered. It is a game paradigm, ironically similar to modern life, in which the performer is challenged to remain focused to produce the correct brain states while distracted by the fact of being on stage and by the glitchy sound patterns and flickering visuals projected onto him. In

[1] The performer has been synchronizing his sleep cycle to the performance time for few days before and started sleeping a few hours before the performance

[2] Butoh is the collective name for a diverse range of activities, techniques and motivations for dance, performance, or movement inspired by the Ankoku-Butoh movement. It typically involves playful and grotesque imagery, taboo topics, extreme or absurd environments, and is traditionally performed in white body makeup with slow hyper-controlled motion, with or without an audience. There is no set style, and it may be purely conceptual with no movement at all. Its origins have been attributed to Japanese dance legends Tatsumi Hijikata and Kazuo Ohno (Barber, 2006).

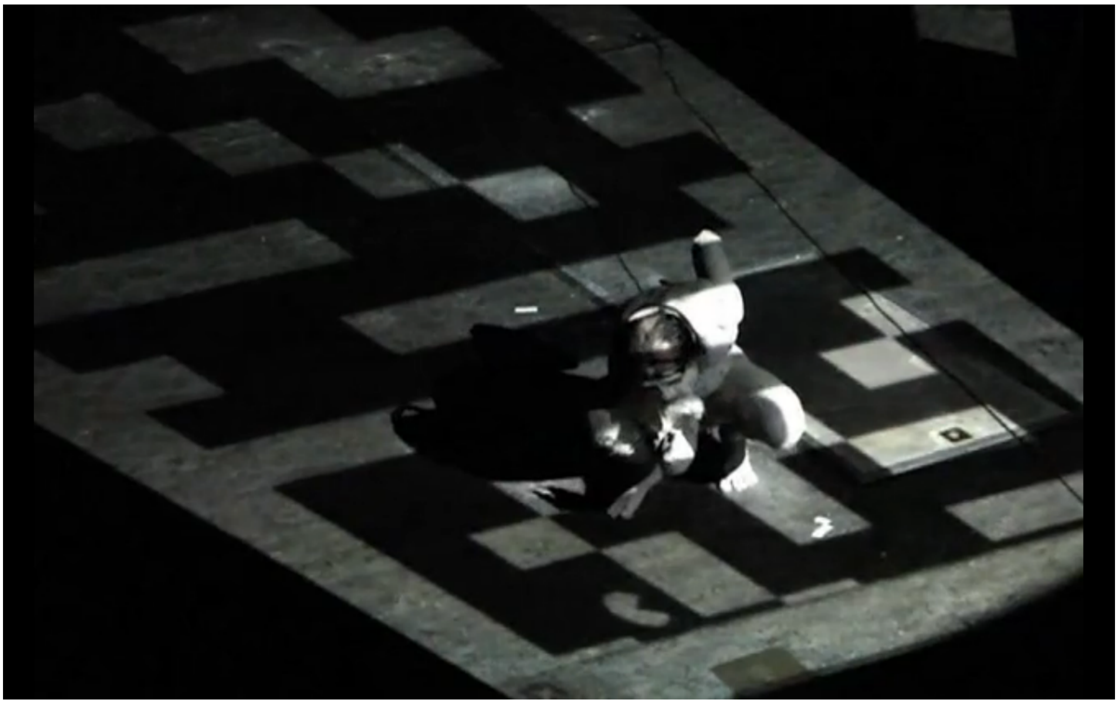

Figure 5.4: Image from the second part of *Fragmentation*. The Butoh dancer wearing the EEG headset moves the virtual avatar (pacman in the bottom of the screen) towards the end of the maze projected onto the stage.

this part I use the temporal analysis of signal pattern recognition. The system is trained to recognize three thoughts of the performer that move the avatar forward, turn it left, and turn it right. The whole structure of the composition and the duration of each individual scene depend on the performerÕs ability to concentrate because the musical and visual scenes are connected to the position of the avatar in the maze. On top of this, the amplitude of brain activity is also dynamically mapped to parameters of individual synthesizers that act as soloist. In this way the performer's brain controls both a soloist instrument as well as the surrounding structure of the piece achieving both goals of a varying musical result and the possibility to listen to the protagonist brain signal.

5.4 Final Considerations

5.4.1 A hybrid mapping

Through the techniques of pattern recognition, both in the temporal and spectral domains, the system achieves a reduction of possible control variables from the complex input sensor data. Using definitions by Rovan et al. (1997), these methodologies introduce a *convergent mapping* that brings simplicity of control, which is required to stabilize the intrinsic noisiness of the EEG. Still, in order to

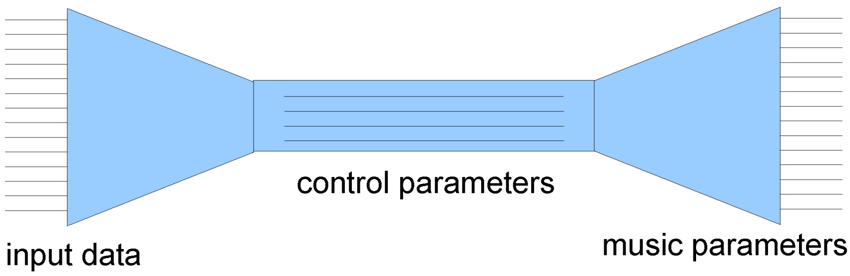

Figure 5.5: Scheme of the hybrid mapping used. The complex input data is reduced from the sensor input to the few control parameters and expanded again using divergent mapping to achieve expressivity.

obtain some expressivity, I needed to map the few control parameters to the multiple synthesis and structural parameters in the music through a *divergent mapping*. The result is hybrid mapping in which the pattern recognition is an intermediate phase to clean the signal from noise and select few stable control parameters. Through out the composition dynamic mapping is also used to reach more control and sound variability for the soloist parts.

5.4.2 Effects on the performer

Fragmentation implies a high workload for the performer. He requires lots of training first to understand what of concepts he must think of to create reliable results, which are repeatable on stage. Experimentation showed some preferred candidates that included imagining specific motor reactions, such as moving an arm or visualizing a specific body position. Often right or left body actions proved to trigger reliable brain patterns that are rather stable over time. The performer has to also learn how to concentrate to consistently and quickly reproduce the same thoughts or brain states over time. Finally, he has to learn to reproduce these results in different rehearsals (possibly weeks away), on stage, in distractive and emotionally challenging contexts. Achieving such a level of concentration and accuracy is not common, and for this reason I decided to work with a Butoh dancer. The Butoh discipline paradoxically require the abandonment of mental distractions so that clear thinking is more easily achievable.

In the specific context of *Fragmentation*, the performer has to concentrate on several actions like soloist and structural control that are abstract from the distractive lights and glitchy sounds, controlling the avatar and also performing a Butoh dance. The performer is free to choose how to handle the balance of all these elements, playing between rationality, emotions and irrational distraction as in real life. The whole performance is conceived to challenge the performer in this arena of elements and use EEG as a microscope to magnify such balance or balance loss for the audience.

5.4.3 Effects on the audience

Thanks to the several elements, the audience is in a position to imagine or place themselves in the performer's state of mind. In the first part, the imposed actions have been selected to determine completely different internal states and addressing different parts of the human being: soul, with a trance-like state during the deep sleep phase; brain, with concentration while solving a rational problem; and body, with the motor movement efforts while jogging. The music is conceived to enhance the audience's expectations and evoke interpretations of what is happening.

In the second part, the performer's thoughts control the virtual avatar. The audience can relate to what is happening and build expectations for every move, predicting the direction of the next step in the maze, through to the quickest way to reach the exit. The numerous EEG control mistake are transformed into an element of the aesthetics: they generate smiles or frustration in the audience, similar to what one might experience during a football game. The errors and effort of the performer, materialize the gesture, making the performance more human. Anyone can understand what the performer is trying to achieve with his brain at any instant.

5.4.4 Mind control types

Different degrees of control are displayed, and control increases progressively through the piece. In the first part the control of the performer is rather passive. His brain state is tuned from the outside, by the actions he has to accomplish. This control is similar to typical performances using spectral analysis in which brain states are connected to some synthesis engine. The new aspect concerning control here is the possibility to affect music elements in two layers: with spectral recognition to choose the sections, and with signal amplitude to control macro parameters inside each section.

The second part of *Fragmentation* addresses a more abstract type of control that is more rational. The performer really intentionally decides what actions to follow, which can accelerate the structure or lose timing. Part of his signal is directly sonified (using the least modification possible to make it just audible) to allow the brain emerge as a soloist to satisfy the ears of whoever wants to hear what the brain signal can sound like.

During testing, I realized that pattern recognition allows some degree of control but unpredictable external causes or simply a minimum distraction would create insurmountable disturbance in the system. The thematic choice of concentration in modern society and the metaphor of a video game helped solve the problem by translating it into an artistic question. The presence of a video game makes the whole performance more interesting and challenging, both for the performer and for the audience. The lack of control in this way becomes a positive element instead of a obstacle.

It can sometime happen that EEG control as implemented in this thesis works particularly well. The use of pattern classification especially in the temporal domain produces a rational conscious and voluntary control that has some of the characteristics of thought. Still, is it still called thought when what we actually measure is electrical brain activity? Is it possible that new technologies in conjunction with advanced statistical tools can let us bridge the gap between the material and the immaterial? I am trying to be careful not to fall into the sensationalisms of the media about brainwave music but the ontological limit between mind and brain appears more and more blurred the more sharp the analytic tools are. Wearing an EEG helmet and driving a virtual avatar in a maze seems to go beyond what is just electrical signals. There is materialized intention, it is no longer some patching of signals to some parameter. What should we call this materialized intention: brain pattern or thought? The first is a physical manifestation of the second, but what ontological barrier separates the two?

5.4.5 Limitations and possible extensions

The choice of the performer is quite important. Most of the constructors, composers, or programmers of EEG-software systems from the 60s until recently are also the actual performers. This choice can raise the doubt about the existence of some "hidden trick behind the curtains". For this reason, I chose to perform the first part, and use another performer for the second part of the performance. The change of people shows that different persons can reliably control the composition and that the system is robust and flexible enough to adapt to different subjects. This is not only a evidence that there is no trickery in its behavior, but also shows the possibility to adapt it to create an interactive installation. This conclusion is especially true in the second part of the performance since it is already a sort of game.

Specific problems are still present. Most notably, the invisibility of the brain is partially solved, but it still seems difficult to connect the musical variations to the brain itself. This can be related to the fact that both brain and music are two invisible entities. So, both music and brain must be made visible to establish a visible link. The attempt of using a soloist instrument and a structural control seem to help at least partially to create both an interesting, slowly evolving background and a rapid foreground that is more representative of the brain. A new algorithmic solution may find a better way to embody the structural and soloistic control in a more organic way.

6 Conclusions

EEG music started and developed in the 60s and 70s, mainly in the United States with pioneering experiments by Alvin Lucier, Richard Teitelbaum and David Rosenboom. These three authors adopted three very personal approaches setting the aesthetic basis for the later experiments: Lucier directly sonifyied the non-manipulated EEG signal; Teitelbaum used EEG as a voltage control unit for synthesizer parameters; Rosenboom implemented algorithms for advanced brain signal analysis to detect specific brain processes and allow some degree of predictability.

The aesthetics and technology used during their performances does not seem to have evolved much in the modern times. The lack of evolution has happened despite the advent of digitalization and the possibility to easily implement statistical and analytical methods of signal processing, and the availability of faster computers with larger memory storage units. Contemporary artists still very often approach the brain as a black box from which it is possible to extract some sort of uncontrollable electrical signal to influence music synthesis parameters. Also the performance aesthetic frequently lack of personal exploration and is exemplified by the very common meditative metaphor of having the performer concentrating alone on stage.

Given such a setting, the intrinsic contradictions of the EEG sensors emerge, often frustrating the audience that cannot take part in the expected "telekinetic magic". The performer's gesture is dematerialized through the invisible brain signal, which is the fundamental element for telekinetic control. As a direct consequence though, the audience has nothing more to observe, the music produced is completely abstracted from any visible cause-effect relationship. Consequently it leaves no cues for the audience to understand what is being controlled. To a certain degree, this problem is related to all computer music. The algorithms hidden behind a screen take away any understanding from the audience. The EEG represents the very extreme of such a case since even the most minimal actions by the performer are erased from the stage and it is only the signals and potentials between the scalp and the captors that is left of the performer's gesture. The final result is as much as an ecstatic experience for the performer as much as a frustration for the observer expecting to assist to a materialization of the brain.

This effect is the consequence of substituting the brain signal instead of using brain control as the real material of the oeuvre d'art. For this reason, it makes much more artistic sense to use EEG live on stage instead of using it to record a brain signal in non-real time for later processing. However, even when conceiving of live performances, artists often focus on brain signals and neglect considering the impact from the EEG sensors. For example, artists forget to consider the implications presented by the EEG sensors for the audience, or think how to transfer some EEG information of what's happening.

Another cause of audience's frustration is connected to the artist's lack of technical knowledge to extract relevant information from the brain signal. Understanding some of the brain features is a way to reach more systematic control, which can open more creative use of the brain signal and probably suggest alternative visual strategies to display new aspects of the brain to the audience.

David Rosenboom first exposed the necessity of embedding some modelling of brain activity into the system to have a possible partial representation of what the brain does. Rosenboom's work is a landmark in the field of BCI for musical applications, as it indicates that the notion of thought-controlled musical systems is indeed possible. The sophistication of such a system is largely dependent upon its ability to harness the EEG signal and to devise suitable generative music strategies.

6.1 Personal techniques

Early in the development of this project it had become obvious that most current methods and practices of EEG data acquisition and processing were utterly inadequate for the level of discrimination that was required in the proposed framework. A major problem in EEG research is the enormous amount of raw data that is being produced and the way of making sense of such huge amount of numbers. These technical problems consequently limit the aesthetic possibilities constraining the field of EEG art to an eternal state of very slow development. Despite the sensationalistic claims of media and some researchers and composers, very few algorithms successfully connect mind to music. Usually what happens is that the use of hardware is able to extract (sometimes doubtfully) measures of the brain's electrical activity.

In the previous chapter, I exposed my personal approach in such direction to solve the intrinsic technical and artistic limitations of brainwave music applications. Using correlation in several instances of brain signals, I trained the system to extract patterns connected to specific mind states and use pattern recognition algorithms to detect similar patterns during the live performance. These techniques allowed conscious and rather reliable control of three system variables in a non-synchronous way. The three system variables are used to control the displacement of a virtual avatar in a maze with three functions: left turn, right turn and moving forward. Depending on the position in the maze sonic events are triggered, stopped, or modified. Through a simple dimensional displacement metaphor, I mapped the basic system of three variables to the complex environment of a musical composition. In doing so the structure and duration of the composition was completely dependent on the performer's ability to concentrate and produce the mind states that led the avatar out of the maze. Furthermore, this method allows the audience to build expectations about where the avatar should be moving to. Also the audience can verify how difficult is the brain control depending on how concentrated is the performer and on how the performer controls the avatar. As a result the audience feels more involved in a more theatrical setting than the usual meditative performance.

What has really been captured in the stored brain patterns is still an open ontological question. Are these just simple values of electrical activity dispersed over the 14 EEG sensors or are these values possibly capturing and recognizing some aspects of real thoughts? Are we still dealing with brain materialism or are we bridging into the mind and consciousness? Compared to the noisy and slow spectral analysis, the surprising reliability of the system lets the user often wonder about the possibility to one day reach detection of proper thought and use them for driving processes as imagined by J. J. Vidal in his first articles on Brain Computer Interfaces.

Despite the fascination and the possibility offered by modern statistical methods such as pattern recognition and machine learning, three are still few who consider EEG as a proper music controller. This observation is particularly true when considering EEG's limited reliability compared to a simple joystick. The unpredictable nature of EEG means that it can effectively be adapted to control simple compositional processes, which are not crucial for the aesthetics of the whole composition and involve couple of variables. It can be integrated as a part of a more complex setup beside with other more complex and stable controllers.

Despite its low reliability, the strong expectations that EEG rises in the audience permeate EEG with an evocative and theatrical power that normal controllers do not have. This aspect opens up a dimension of fascination that in my opinion has much more interest than the controllability offered by its sensors. It is every performer's challenge how to handle such power, finding a way to visualize the mind control and allow the audience to imagine and perceive some aspects of the brainpower.

Moreover, the presence of such technology can open up ways of exploring new themes. So far, EEG has been used to analyze aspects of relaxation and meditation. In my personal research, the possibility of using specific brain patterns to control a video game suggests the possibility to explore the balance between concentration and distraction by asking a performer to execute tasks in chaotic situations. Future work in possession of more evolved techniques can possibly investigate and display emotions or other more subtle and removed internal states.

6.2 Future research

From a short analysis of the EEG art field, it is evident there is a need for more research to achieve a better description of the brain signal characteristics to extend the amount of brain control. Such advancement would be fruitful to open more expressive possibilities for artists, as well as possible insight for scientist. Indeed, the contributions of these two fields are arguably interdependent. New research has to be brought forward both on the hardware and on the software side. New systems or strategies are needed to reduce the noise in the detected signal. There are already new sensors on the market that use dry contact in the form of micro needles that pass through the scalp skin to achieve closer contact with the electrical activity.

Future research can also implement better methods for pattern recognition of EEG signals. There are more complex pattern recognition algorithms than those proposed in this thesis, such a ada-boost, support vector machine, or neural networks, among others. These methods have proven to be robust in other situations and may be the right candidates to extract reliable signal patterns to further reduce noise fluctuations. Implementing feature extraction algorithms from the raw signal can further reduce the influence of external noise by analyzing tendencies of feature values instead of the signal itself. It would also be useful to apply these methods while estimating the sensors relevance depending on the location on the scalp. In this research all sensor contributions have been weighted in the same way but it is reasonable to assume that certain scalp zones transmit more relevant activity for specific brain states over other zones.

All these methodologies can be applied and measured several times with different conditions to filter out uncorrelated noise and create a robust database. This database could be used for rapid training of algorithms and may even lead to scientific investigations. For example it would be interesting to know if it is possible to bridge patterns between individuals, exploring if different people produce similar patterns when thinking of simple ideas such as colors or shapes. The experiments during this thesis showed no correlation between patterns of different users. Even within the same individual brain patterns slowly shift making results rather jittery from session to session and forcing a recalibration of the system prior to every performance.

Another important direction of future research could be the experimentation with different mental states to establish which thoughts have more clear and defined patterns. For example imagining specific physical actions, colors, recalling past events, or imagining environments in a sort of daydreaming scenario. In such cases, it would be extremely beneficial to tune a thought and its result to the same semantic category, such as imagining raising pitch to actually raise the pitch of an instrument. The problem in this case is the level of abstraction with these thoughts. Imagining such a task is probably more delicate and unstable than thinking about a red circle, not to mention visualizing something more vague, such as event density or musical gestures.

Finally, artists have to find more creative ways of applying brains signal to make brain control more visible, exploring new themes, and deviating from past tradition in a personal way. For example, experimenting with performers who by nature have higher levels of concentration or brain control (e.g. mediums, mathematicians, individuals affected with autism), or lower levels of concentration or brain control (e.g., animals, children, or individuals with attention impairment). It might also be interesting to explore extreme scenarios and situations that are supposed to alter whole body activities such as deep dreaming or sleep deprivation states, use of different drugs, analyzing the signals during sexual intercourse, visual flickering, or electrical stimulation.

Bibliography

Adrian, E. D. and Matthews, B. H. C. (1934). The berger rhythm: potential changes from the occipital lobes in man. *Brain*, 57.

Alvarez, G. A. and Franconeri, S. L. (2007). How many objects can you track? evidence for a resource-limited attentive tracking mechanism. *Journal fo Vision*, 7(13:14):1–10.

Anderson, C. W. and Sijercic, Z. (1996). Classification of eeg signals from four subjects during five mental tasks. *In Solving Engineering Problems with Neural Networks: Proceedings of the International Conference on Engineering Applications of Neural Networks.*

Arslan, B., Brouse, A., Castet, J., Filatriau, J. J., Lehembre, R., Noirhomme, Q., and Simon, C. (2005). Biologically-driven musical instrument. *eNTERFACE'05 workshop - final project report.*

Auslander, P. (2008). *Liveness: Performance in a Mediatized Culture*. Routledge.

Ballora, M. (2011). Opening your ears to data. Retrieved March 15, 2011 from http://www.youtube.com/watch?v=aQJfQXGbWQ4.

Barber, S. (2006). *Hijikata: The revolt of the body.* Solar Books.

Berger, H. (1931). Über das elektrenkephalogramm des menschen. *Arch. Psychiat.*, 94:16–60.

Birbaumer, N., Flor, H., Ghanayim, N., Hinterberger, T., Iverson, I., Taub, E., Kotchoubey, B., Kübler, A., and Perelmouter, J. (1999). A brain-controlled spelling device for the completely paralyzed. *Nature*, 398:297–298.

Broek, C. D. (2012). Staal hemel project website. Retrieved March 15, 2011 from http://www.staalhemel.com.

Cadoz, C. (1988). Instrumental gesture and musical composition. *Proceedings of the International Computer Music Conference.*

Cadoz, C. and Wanderley, M. M. (2000). *Gesture-Music*, volume Trends in Gestural Control of Music. M. Battier and Marcelo M. Wanderley.

Casalegno, M. (2012). Personal website. Retrieved March 15, 2011 from http://www.mattiacasalegno.net.

Chadabe, J. (2002). The limitations of mapping as a structural descriptive in electronic instruments. *Proceedings of the Conference on New Instruments for Musical Expression*.

Chechile, A. (2012a). Brain wave music. Retrieved March 15, 2011 from http://www.youtube.com/watch?v=C8Xd8Hr _r8w.

Chechile, A. (2012b). Personal website. Retrieved March 15, 2011 from http://www.alexchechile.com.

Chechile, A. A. (2007). *Music Re-Informed by the Brain*. PhD thesis, Rensselaer Polytechnic Institute Troy, New York.

CNMAT (2012). Retrieved march 15, 2011 from http://opensoundcontrol.org. Berkeley Center for New Music and Audio Technology.

Collins, N. (2009). Introduction of Alvin Lucier's music. Presentation at the Dag in de Branding Festival, 29 May 2009, Den Haag, The Netherlands.

de Campo, A., Höldrich, R., Eckel, G., and Wallisch, A. (2007). New sonification tools for eeg data screening and monitoring. *Proceedings of the International Conference on Auditory Display*.

Emotiv (2012). Company website. Retrieved March 15, 2011 from http://www.emotiv.com.

Faraldo, A. (2009). Bridging opposites. understanding computer-based free improvisation. Master's thesis, Institute of Sonology, The Hague.

Filatriau, J. J. and Kessous, L. (2008). Visual and sound generation driven by brain, heart and respiration signals. *in Proceedings of the International Computer Music Conference*.

Fung, J. (2012). Personal research page. Retrieved March 15, 2011 from http://eyetap.org/ fungja.

Fung, J. and Mann, S. (2012). Brain wave music in the key of eeg. Retrieved March 15, 2011 from http://www.youtube.com/watch?v=Ff-Dmlreg4I.

Grieson, M. (2012). Brain computer music interface. Retrieved March 15, 2011 from http://www.youtube.com/watch?v=kNp71xBDcMA.

Grieson, M. and Peters, F. (2011). Finn Peters music of the mind. Retrieved March 15, 2011 from http://www.youtube.com/watch?v=epT16fbf4RM.

Grieson, M. and Webb, A. (2011). Thinking up beautiful music. Retrieved March 15, 2011 from http://news.bbc.co.uk/2/hi/technology/7446552.stm.

Haill, L. (2012). Tunes on the brain: Luciana Haill's eeg art. Retrieved March 15, 2011 from http://www.wired.co.uk/magazine/archive/2010/09/play/tunes-brain-luciana-haill-eeg-art.

Hinterberger, T. (2007). Orchestral sonification of brain signals and its application to brain-computer interfaces and performing arts. *Proceedings of the International Workshop on Interactive Sonification.*

Hinterberger, T. and Baier, G. (2005). Parametric sonification of eeg in real time. *IEEE Multimedia*, 12(2):70–79.

Hjorth, B. (1970). Eeg analysis based on time series properties. *Electroencephalography and Clinical Neurophysiology*, 29:306–310.

IBVA (2012). Product webpage. Retrieved March 15, 2011 from http://www.ibva.co.uk.

Kubler, A. and Muller, K. R. (2007). *An Introduction to Brain-Computer Interfacing. In Toward Brain Computer Interfacing.* The MIT Press.

Lucier, A. (1995). *Reflections, Interviews, Scores, Writings, 1965-1994.* Musik-Texte.

Lucier, A. and Simon, D. (1980). *Chambers. Scores by Alvin Lucier, Interviews with the composer by Douglas Simon.* Connecticut: Weslayan University Press.

Mealla, S., Valjamae, A., Bosi, M., and Jorda, S. (2011). Listening to your brain: Implicit interaction in collaborative music performances. *NIME proceedings.*

Miranda, E. R. (2012). Guy plays piano with his brain. Retrieved March 15, 2011 from http://www.youtube.com/watch?v=o5If0H2wyTI.

Miranda, E. R. and Boskamp, B. (2005). Steering generative rules with the eeg: An approach to brain-computer music interfacing. *Proceedings of Sound and Music Computing.*

Miranda, E. R. and Brouse, A. (2005). Interfacing the brain directly with musical systems: On developing systems for making music with brain signals. *Leonardo*, 34(8):331–336.

Miranda, E. R., Durrant, S., and Anders, T. (2008). Towards brain-computer music interfaces: Progress and challenges. *Proceedings of International Symposium on Applied Sciences in Bio-Medical and Communication Technologies.*

Miranda, E. R., Roberts, S., and Stokes, M. (2004). On generating eeg for controlling musical systems. *Biomedizinische Technik*, 49(1):75–76.

Miranda, E. R., Sharman, K., Kilborn, K., and Duncan, A. (2003). On harnessing the electroencephalogram for the musical braincap. *Computer Music Journal*, 27(2):80–102.

Misulis, K. E. (1997). *Essentials of Clinical Neurophysiology.* Boston: Butterworth-Heinemann.

Moore, B. C. J. (2003). *An introduction to the psychology of hearing.* London, UK: Academic Press.

NativeInstruments (2012). Company webpage. Retrieved March 15, 2011 from http://www.nativeinstruments.com.

Neurosky (2012). Company webpage. Retrieved March 15, 2011 from http://www.neurosky.com.

Oliveros, P. (1984). *Software for People. Collected writings 1963-1980.* Baltimore: Smith Publications.

OpenEEG (2012). Project website. Retrieved March 15, 2011 from http://www.openeeg.com.

Pelvig, D., Pakkenberg, H., Stark, A. K., and Pakkenberg, B. (2008). Neocortical glial cell numbers in human brains. *Neurobiology of Aging*, 29 (11):1754–1762.

Peters, B. O., Pfurtscheller, G., and Flyvbjerg, H. (1997). Prompt recognition of brain states by their eeg signals. *Theory in Biosciences*, 116:247–258.

Riad, Y. (2012). Two.0: Presentation for radio 4 on april 20, 2011,. Institute of Sonology, The Hague.

Robels, C. (2012). Personal website. Presentation at the conference Live Electronics and the Traditional Retrieved March 15, 2011 from http://www.claudearobles.de.

Rosemboom, D. (1987a). Cognitive modeling and musical composition in the twentieth-century: A prolegomenon. *Perspectives of new music*, 25(1,2).

Rosemboom, D. (1987b). A program for the development of performance-oriented electronic music instrumentation in the coming decades: "what you conceive is what you get". *Perspectives of new music*, 25(1,2).

Rosenboom, D. (1984). On being invisible: I. the qualities of change (1977), ii. on being invisible (1978), iii. steps towards transitional topologies of musical form (1982). *Musicworks, 28*, 28:10–13.

Rosenboom, D. (1990). *Extended Musical Interface with the Human Nervous System, Assessment and Prospectus.* Leonardo Monograph Sries: International Society for the Arts, Sciences and Technology (ISAST).

Rosenboom, D. and Teitelbaum, R. (1974). *Biofeedback and the Arts, Results of Early Experiments.* Aesthetic Research Centre of Canada, Toronto, Canada.

Rovan, J. B., Wanderley, M. M., Dubnov, S., and Depalle, P. (1997). Instrumental gestural mapping strategies as expressivity determinants in computer music performance. *Proceedings of the AIMI International Workshop*, pages 68–73.

Schloss, W. A. (2002). Using contemporary technology in live performance: The dilemma of the performer. *Journa Of New Music Research.*

Singh, I. (2006). *Textbook of human neuroanatomy.* Jaypee Brothers Publishers.

Snyderphonics (2012). Product webpage. Retrieved March 15, 2011 from http://snyderphonics.com/order.htm.

Stockhausen, K. (1957). *... wie die Zeit vergeht ...* Die Reihe 3 (“Musikalisches Handwerk”).

StudiumGeneraleGroningen (2012). Behind the music of the mind. Retrieved March 15, 2011 from http://studium.hosting.rug.nl/nl/Archief/Jaar-2011/Series-jaar-2011/Behind-the-music-of-the-mind.html.

Supercollider (2012). Software webage. Retrieved March 15, 2011 from http://supercollider.sourceforge.net.

Tenney, J. (1988). *Alvin Lucier.* Connecticut: Ezra and Cecile Zilkha Gallery.

Tononi, G. (2008). Consciousness as integrated information: a provisional manifesto. *Biological Bulletin*, pages 215:216–242.

Vidal, J. J. (1973). Toward direct brain-computer communication. *Annual Review of Biophysics and Bioengineering*, 2:157–180.

von Falkenstein, J. T. (2011a). Presentation at the Research Seminar, the hague. Institute of Sonology.

von Falkenstein, J. T. (2011b). Using self organising maps as a synthesis and composition tool. *CMMAS Ideas Sonicas*, 2(2).

Wentrup, M. G., Gramann, K., Wascher, E., and Buss, M. (2005). Eeg source localization for brain-computer-interfaces. *Proceedings of the International IEEE EMBS Conference on Neural Engineering*.

Wessel, D. (2006). *An Enactive Approach to Computer Music Performance. In Actes des rencontres musicales pluridisciplinaires*. Grame Lyon.

Zimmerman, W. (1976). *Interview with Richard Teitelbaum in Desert Plants: Conversations with 23 American Musicians*. Aesthetic Research Centre of Canada Publications, Vancouver, B.C., Canada.

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