Auditory Display of Brain Oscillatory Activity with Electroencephalography

Andrew Stella

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Master thesis coordinator:

Dr. Sergi Jordà Puig

Master thesis supervisor:

Sebastián Mealla Cincuegrani

Department of Information and Communication Technologies

Universitat Pompeu Fabra, Barcelona

To Laura

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Abstract

Auditory display is a relatively young field that has nonetheless been applied to many different types of research, including data exploration, musical composition and performance and for studying medical conditions such as epilepsy. Sonification, a type of auditory display which can generally be defined as the transformation of data into sound, has been applied to biofeedback systems, computer assisted collaborative work, and astronomy, to name just a few. Despite the considerable amount of recent work involving sonification and biofeedback, it is not clear what types of sonification strategies or mappings are most effective for aiding the perception of brain and body states. This master thesis aims to help answer this question by developing and testing a sonification engine capable of a range of sonification techniques, from audification-the simplest, most direct technique-to more arbitrary or musical mappings. In all, three techniques are presented: a relatively simple and direct approach, a second technique where events or features of the data modulate features of the output sound, and a third technique that could be described as more musical or arbitrary. This sonification system is built using Pure Data, an open-source graphical computing environment. Using the Emotiv EPOC Brain-computer interface headset and a complex chain of signal acquisition and processing software, we tested our sonification system in an experiment featuring 14 subjects. Each subject was brought into a quiet room and fitted with the EPOC device. They were then exposed to a total of 12 different sonification sessions, half of which were in real-time and half of which were placebos. The order of sonifications and placebos was randomized for each subject. Data was gathered using a questionnaire and the recording of physiological data taken directly from the BCI device. Both types of data were used to compare real-time techniques to placebos as well as to one another. While no significant findings were reported with regards to a our sonifications having a greater effect on subjects' state of relaxation, the data do conclude that our parameter-mapping sonification technique is the most relaxing, and thus a good candidate for further study.

KEYWORDS: Electroencephalography, EEG, Sonification, Auditory display, Biofeedback, Neurofeedback, Sound perception, Psychoacoustics, alpha band, music.

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1 Introduction

1.1 Problem Statement

The goal of this work is to determine whether auditory display of brain activity can be coherently perceived as being representative of internal brain and body states. Towards that end, an advanced sonification engine capable of several different auditory display techniques has been developed and applied to brain states using real time Electroencephalogram measures. Sonification can be succinctly defined as the transformation of data into sound [93]. More specifically, sonification can be thought of as turning data relations into perceived relations in an acoustic signal for the purposes of facilitating communication or interpretation [59]. Auditory display has been used in conjunction with physiological signals for a number of purposes over the years, including data exploration, music composition and performance, and computer-assisted collaborative work. However, from the available literature, it is still not clear what types of auditory display techniques or mappings perform best in aiding perception of brain and body states within a biofeedback paradigm.

Electroencephalogram (EEG) is the neurophysiologic measurement of electrical activity produced by the brain [73]. Using electrodes arranged around the scalp, voltage fluctuations resulting from ionic current flows within the brain's neurons can be measured. Commonly, the change in these voltages over time is displayed visually and in real time. Neural activity often possesses a repetitive rhythmic quality, and these rhythms are classified as alpha, beta, theta or delta. In this work we focused on activity in the alpha band, which has been associated with the brain's level of relaxation.

In our system, robust EEG signal was acquired using the Emtiov EPOC wireless EEG headset [3], and streamed at high temporal resolution to a personal computer where the signal was processed and desired channels were filtered. These data were then sent as OSC messages to a second computer which hosted the sonification engine. Once a technique was selected, the resulting sonifications were then played in real time through a set of loudspeakers. Aditya Nandwana, a student in the Interdisciplinary Master in Cognitive Systems and Interactive Media, developed the signal acquisition and processing portion of our system, and was my research partner throughout this project.

In order to test this system, an experiment was devised consisting of twelve two-minute sonification 'sessions', divided into two sets of six. Study subjects were exposed both to real time sonifications as well as placebo recordings. The order of the sonifications was randomized. Measurements were taken in two ways: first, subjective responses from each subject were recorded in the form of a questionnaire. Second, objective measurements of each subject's alpha activity were recorded during the experiments.

1.2 State of the Art

In the following sections, an overview of concepts and previous research related to this thesis is presented. Basic neuroanatomy and EEG concepts are discussed, followed by a historical look at sonification, as well as how sonification has been used in the arts, in EEG research, in music composition and performance, and in a biofeedback paradigm.

1.2.1 Anatomy of the Human Brain

The human central nervous system (CNS) is composed of three main parts: the cerebrum, the cerebellum and the medulla oblongata, also referred to as the brain stem. The cerebrum, which is of concern to the research presented in this thesis, can be divided into two hemispheres, and each hemisphere contains a frontal, parietal, occipital and temporal lobe.

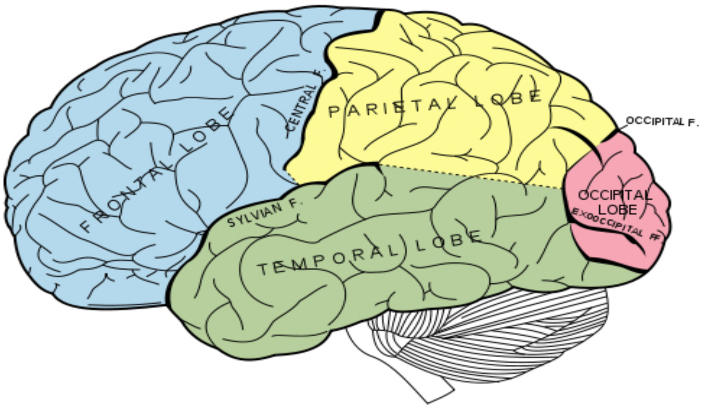


Figure 1: The four lobes of the human brain[Gray's Anatomy].

The frontal lobe, which is the largest of the four, is situated at the anterior tip of the brain and extends to the central sulcus, which separates it from the temporal lobe. The frontal lobe is responsible for such things as primary motor functions as well as what are called executive functions: personality, insight and foresight [75].

The parietal lobe, situated in the middle of the brain, is generally associated with three general functions:

- Initial cortical processing of proprioceptive (sense of position) and tactile information.
- Comprehension of language
- Spatial orientation and directing attention.

High-order processing of visual information and auditory information is handled by the temporal lobe, which also plays an important role in learning and memory.

Lastly, the occipital lobe can be found in the rear of the skull, and is the smallest of the four lobes. It is more or less exclusively associated with visual functions.

1.2.2 Electroencephalography

Electroencephalography, or EEG, refers to the recording of electrical activity within the cerebral cortex [73] Specifically, voltage fluctuations resulting from ionic current flows within the brain’s neurons are being measured. Commonly, these measurements are taken by attaching electrodes to the scalp. Higher voltage readings can be obtained by placing the electrodes directly on the surface on the brain, but such readings would require an invasive surgical procedure to be performed on the subject, and are thus clearly not suitable for many types of research. Scalp electrodes are generally arranged according to the 10-20 system, which is an internationally recognized method for use in EEG tests and experiments [102].

Hans Berger, a German psychiatrist, is credited with making the first recording human EEG recordings. The result was a signal that displayed a clear oscillatory pattern. The shape and pattern of the signal were found to differ based on the location of the electrodes on the scalp. Furthermore, the mental and physical state of the subject was found to affect the pattern and the amplitude of the recorded signals. States of attention or relaxation, for example, exhibit certain characteristics in the EEG. Whether a subject's eyes are open or can also have a strong effect [7].

Figure 2: The first known recording of a human EEG signal. The upper portion is the EEG signal and the lower portion is a 10Hz timing signal[64].

1.2.2.1 EEG Rhythms

EEG signals taken from electrodes on the scalp tend to have amplitudes around 100 μV, while those taken on the surface of the brain have generally have amplitudes of 1-2 mV[64]. With regards to frequency, the full signal bandwidth ranges from 0.5 Hz to 30-40 Hz [86]. Classification of EEG signals is made based on frequency, and historically, five types of rhythmic activity have been used: alpha(α), beta(β), theta(θ), delta(δ) and gamma(γ). There is no precise agreement on the frequency range for each type.

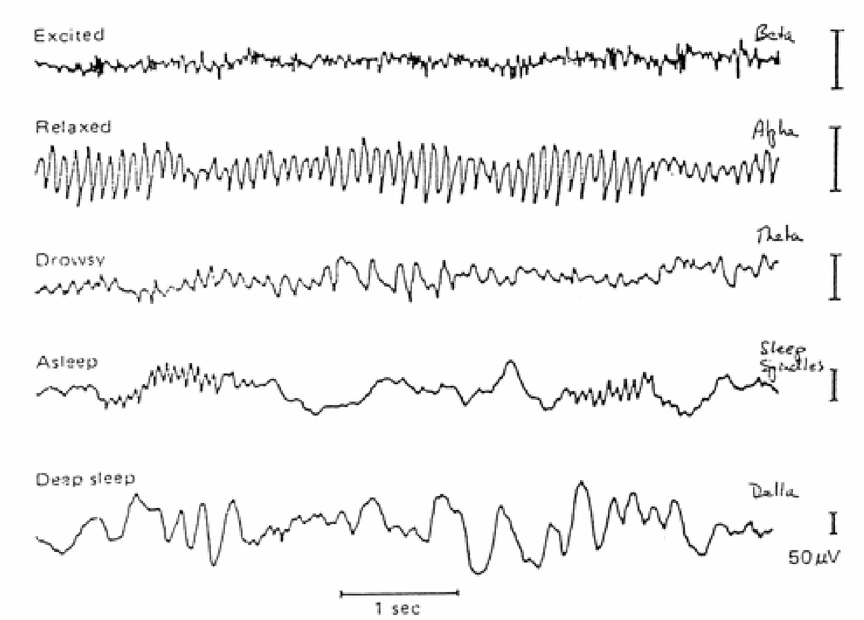


Figure 3: Examples of different types of osciallatory EEG activity[4].

Delta Rhythms - Usually up to 4 Hz, these are waves of high amplitude and are picked up from the frontal cortex in adults and posteriorly in children. The state is usually that of slow wave sleep in adults, although they are detected during some continuous attention tasks as well.

Theta Rhythms - Between 4-8 Hz normally, these rhythms are detected in locations not related to the task at hand. They are frequently observed in young children, during phases of drowsiness or arousal and idling.

Alpha Rhythms - of particular relevance to this study, alpha rhythms oscillate at approximately 7-13 Hz and are found on either side of the posterior regions of the head. They are higher in amplitude on the non-dominant side. The central sites (C3-C4) are at rest. Alpha waves are particularly prominent in subjects who are relaxed and awake with their eyes closed, alpha suppression takes place in open-eye conditions.

Beta Rhythms – These are fast rhythms oscillating between 14-30 Hz. The amplitudes are relatively low. Beta rhythms are associated with an activated cortex and can be observed during certain sleep stages. The main points of observation are the frontal and central regions of the scalp.

Gamma Rhythms – Gamma rhythms are fast rhythms oscillating above 30 Hz indicative of a state of active information processing in the cortex [76].

1.2.3 Sonification-Historical Background and Development

The most commonly agreed definition of sonification comes from the *Sonification Report: Status of the Field and Research* Agenda [59]:

"Sonification is the use of non-speech audio to convey information. More specifically, sonification is the transformation of data relations into perceived relations in an acoustic signal for the purposes of facilitating communication or interpretation."

Despite the long history of sonification in science, as we will see, existing definitions of sonification were unsatisfactory until the 1990s. Creative individuals such as artists and musicians have long been using data for compositional purposes. However, for these types of works to be denoted as sonification, a case can be made for a more detailed definition, clearly stating what criteria must be fulfilled for a sound to be called a sonification [36]. Such a definition was presented by Thomas Hermann, one of the most important contemporary researchers in the field, in a 2008 paper [37]:

"Any technique that uses data as input, and generates(eventually only in response to additional excitation of triggering) sound signals may be called sonification, if and only if:

A) the sound reflects properties/relations in the input data.
B) the transformation is completely systematic. This means that there is a precise definition of how interactions and data cause the sound to change.
C) the sonification is reproducible: given the same data and identical interactions/triggers the resulting sound has to be structurally identical.
D) the system can intentionally be used with different data, and also be used in repetition with the same data.

It is necessary at this point to distinguish two similar, sometimes overlapping and often confusing terms: sonification and audification. Sonification would be any technique that satisfies the above definitions. Audification, on the other hand, is just one type of sonification technique. It is often described as the simplest of such techniques [25][40]. Thus, all audifications are sonifications, but not all sonifications are audifications. Audification has been defined by Gregory Kramer as: "The direct playback of data samples..." [57]. He and Walker later went on to extend the definition: "Audification is the direct translation of a data waveform into sound" [93]. Yet another useful description is contributed by Dombois and Eckel in [25]: "

Audification is a technique for making sense of data by interpreting any kind of one-dimensional signal (or of a two-dimensional signal such as a data set) am amplitude over time and playing it back on a loudspeaker for the purpose of listening."

Audification can include frequency modulation to shift the sound into an audible range, looping, conversion to the analog domain, and amplification. Other than the frequency shifting, there does not need to be other intermediary elements. Filters and other processing techniques can be used to isolate certain elements, but no sound-generating elements are introduced [58]. Given the simplicity of this technique, audification is often selected as a first approach for auditory investigation [25]. Many of the earliest uses of sonification, some described in this text, utilized basic audification techniques.

While the broadest historical overview of sonification and the auditory display of data could certainly include events reaching back thousands of years, a more focused approach requires concentrating in the late twentieth and early twenty first centuries. Rapid developments in computing power and sound synthesis technology contributed to the advancement of the field during this period [58]. However, it is instructive to mention several important inventions from the nineteenth century that are nonetheless of great importance, both in a general sense and specifically in the realm of sonification. The telephone, invented by Alexander Gram Bell in 1876, the phonograph, invented by Thomas Edison in 1877 and, in 1895, the development of radiotelegraphy by Marconi. After all, these inventions mark the beginning of turning sound waves into electric signals, and vice-versa [29]. In addition to important social changes that resulted form the development and proliferation of these technologies, they also inspired and influenced new research in the field of audification. It can be said that Edison was the first to demonstrate intentional audification with the "Time Axis Manipulation" of sound recording data, in 1878 [29]. Importantly, the idea of mediation must be considered in terms of audification and sonification. Since sonification revolves around the idea of data-driven sound, the introduction of media by which this data can be stored or transmitted (electricity, engraved curves on wax cylinders) was vital [25]. In this sense we see that it is possible for all forms of data to be displayed as sound, and the process of listening to data can be said to depend on the data, its conversion, the display technique and issues associated with perception.

Even before the electrical age, important examples of early sonification exist. The invention of the stethoscope by T.H. Laennec represented a use of scientific audification of general acoustical data [61]. This device, which is still in very wide use, is one of the few widely accepted scientific devices that uses audio rather than other types of display. The addition of "interactivity", when Auenbrugger added percussion to the device, created interest in listening to the human body [9]. Other examples of early audification applications involve physical data. Bernstein and Schonlein audified the reaction frequencies of muscles cells in what they described as the "muscle telephone" [17]. Wedenskii, in a 1883 paper, used the loudspeaker from a telephone as the audio display for nerve currents [94]. The Geiger counter, invented by Hans Geiger in 1908, is a good example of the audification of non-acoustic data [25].

Perhaps the first use of Time Axis Manipulation for a scientific application occurred in 1924, when U.S. scientists applied audification to the echo location sounds of bats to make them audible for humans. Sonar, which was originally developed in Great Britain to track submarines, also came from this period. The Vocoder, and its use as a device for encoding sound is also relevant. The SIGSALY system, developed in 1942-1943, utilized the Vocoder as a method for securely transmitting voice audio. The speech signal would be encrypted by another sound, such as noise. Thus, the transmitted signal would sound like random noise, but the receiving station would be able to use the same noise signal to decrypt the original signal [54]. The vocoder has seen further applications in film and popular music in more recent years.

Continuing with the idea that scientific development can be strongly influenced by technology, the development of audio tape by Fritz Pfleumer in 1928 is worth mentioning. This new medium was soon used for storage of various types of data. The types and amount of possible manipulations of this data seem endless with the addition of a recording head, playback head, and forward/backward controls [54]. With sound recorded on magnetic tape, the temporal evolution of the data was now able to be clearly and linearly defined in space.

The year 1934 saw an important landmark in early audification techniques. Physiologists E.D. Adrian and B.H.C. Mathews were the first to document the transformation of human electroencephalogram (EEG) into audio signals. Adrian and Mathews subjectively described the audible changes in Adrian's 'alpha rhythm' (large amplitude waves in the range of 8-13 Hz) depending on his eye activity [7]. This 'alpha rhythm' was originally called the 'Berger rhythm'. Although a rhythmic quality in waves detected from the scalp was first reported in the 1870s, it was Berger who provided the first detailed study of the human electroencephalogram. While he was using, by today's standards, quite crude equipment and instruments, Berger was able to detect relatively large-amplitude oscillations in the EEG signal, especially in the occipital area of the cortex (back of the head). It is believed that the term 'alpha' is used to describe this rhythm simply because this was the first type of wave to be detected [71].

In 1954, Pollack and Ficks published a paper detailing research into using auditory variables to describe quantitative information [80]. Their system was able to convey eight binary variables using the auditory information of tone and noise bursts. Stereo location of the display, as well as total display duration, temporal ratio of tone to noise, pitch area of the noise, pitch of the tone, loudness of the tone, and the pitch/noise alteration rate were selected to encode the eight variables. These multiple variable audio displays were found to perform better than certain single variable displays. Concurrently, they found that further division of existing dimensions does not seem to improve the overall transmission of data as much as increasing the number of display dimensions does. Much current research in auditory display and sonification involves the continuous change of data over time, and the data is often displayed using a real-time system. Clearly, this is far removed from the relatively simple binary variables used by Pollack and Ficks, and the problems and issues encountered by more modern displays are quite different [58].

Speeth used audification of seismic data in a 1961 study, to determine if subjects could distinguish the sound of earthquakes from those of bomb blasts [87]. Seismograms of these events were found to be complex and difficult to differentiate. By speeding up the recordings, which were made on the previously mentioned magnetic tape, the seismic data shifted into a more audible frequency range. The result was a greater than 90% correctness rate for classifying earthquakes versus bomb blasts. As an added advantage found in audification of the data, a day's worth of data could be listened to in approximately five minutes by manipulating the playback speed [25][57].

Along similar lines, Frantti conducted a study asking observers to classify time-compressed audifications of seismic events as earthquakes or explosions [26]. In this study, 66% of events were classified correctly. Variables included in Frantti's study were meant to determine the effect of the listener's receiver operating characteristics, such as the effect of training, the effect of distance, and the effect of horizontal and vertical playback. It was found that using stereo playback could improve performance.

While not a formal study, the work of Chambers, Matthews and Moore at AT&T Bell Laboratories demonstrated a three-dimensional auditory display for encoding data from a scatterplot [22]. Three variables in the data were described with sound using pitch, timbre and amplitude modulation. Changes in the data were represented by chromatic quantization of pitch and adding formants in the timbre. They observed that their system aided in classifying the data.

An industrial use was devised by two German inventors working for M.A.N.-Roland Druckmaschinen Aktiengesellschaft [50]. They developed a system for the auditory monitoring of printing presses, in which various machine parameters could be sent to signal generators, thus creating an innovative type of alarm. Most simply, when predefined thresholds were reached, the signal generators were turned on. More complex implementations were possible as well.

In 1979, Fred Scarf used auditory display to explore data from the Voyager-2 Plasma Wave Experiment. Notably, Scarf was able to get scientifically valuable results using sonification that were not possible using more traditional visual display techniques [82]. Strangely, the success in using sound for data in this instance did not produce much in the way of additional research in this area.

Sonification applied to analytical chemistry was implemented by Edward Young in the early 1980s. He used auditory variables such as loudness, decay time, location within the stereo field and pitch ranges to describe the amount of metal present in given samples. Using no more than two training sessions, study subjects achieved a correct classification rate of 98% when asked to put a given sample in one of four categories [96].

It is important to note that in parallel to the research already described, much work was also being conducted in the development of displays for the visually impaired. Throughout the development of sonification and auditory display as a research discipline, applications that aim to better understand various medical conditions or assist those who suffer from them have been numerous. These applications include acoustic feedback of instrumentation developed at Smith Kettlewell in the 1970s, using sound to represent graphs as described by Mansur et al, and chemistry displays by Lunney [58]. These past efforts have led to contemporary uses of sonification to aid those suffering from epilepsy and various forms of paralysis such as that caused by ALS [19]. These contemporary applications will be discussed in a later section.

A significant early contribution to the field came from Sara Bly. Her doctoral thesis [25] was concerned with classification of non-ordered multivariate data sets. In a data set with *n* dimensions, each data point was represented by an audio event in which *n* parameters were controlled by the data. Possible parameters were loudness, pitch, duration, timbre, attack time, and waveshape. Bly used a multivariate data set, involving the classification of flower species using four measurements per plant. Using sound, most study subjects were able to correctly classify most of the plants. In the same paper, a logarithmic data set was presented, and the logarithmic relationship between frequency and pitch was used to represent it. The exponential variable of earthquake magnitude was encoded in pure frequency and also in loudness and duration. The result was a positive indication that significant features of seismic data could be represented through sound.

Bly conducted formal experiments using multivariate data, which were presented using sound only, graphics only and bimodal displays. Other variables were training methods and the data-to sound mappings. Subjects were tasked with classifying a test sample as belonging to one of two possible sets. The results indicated that auditory display was as effective as visual display, and that the combined display outperformed both.

In research carried out by Mezrich, Frysinger and Slivjanovski, dynamic representations of economic indicators was attempted using a mixture of visuals and sound for this multivariate data. In their work, each data point in the n-dimensional space was represented in a visual ‘frame’ with n tones. The visual components represented location and size of data, while the musical notes changed in pitch. Other sound variables were held constant. The analyst, in this case, deals with a sample from the time series rather than the entire data set at one time. These samples are showed successively, as in a film. This display technique seemed to assist in global pattern recognition, using fewer data points than those required when using an overlaid display [69]. In an extension of this research, Frysinger tested the display technique to determine the degree to which auditory display is enhanced by simultaneous visual display. He found that data interpretation performance depended on the assigned task, but also that the combined auditory and visual display was superior to auditory only display. Specifically for trained-pattern detection, Frysinger found that dimensionality was not a factor, and the combined display had essentially the same performance as the auditory-only display [69]. This suggests that visual display did not contribute in a significant way to trained pattern recognition. Given that the detection of patterns is important in data analysis tasks, and certainly in those involving the detection and extraction of patterns in EEG signals, this result is significant. Auditory displays, it could be said, can offer more than just a companion or an enhancement to visual displays [58].

In 1985, the small group of researchers involved in auditory display were gathered to present their work at the CHI '85 Computer Human Interface conference. Included in this group were Bly, Frysinger, Lunney, Mansur, Mexrich and Morrison [58], and the moderator of their panel was Bill Buxton. This marked the first time that a national conference session was focused exclusively on non-speech audio for the representation of data. Despite the excitement of the first true gathering of the key researchers in this relatively young discipline, problems such as scarce research funding impeded further progress for much of the following decade.

The proliferation of personal computing in the 1980s led to the development of non-speech auditory elements for computer interfaces. Gaver's SonicFinder [28] and research at Apple Computer's Advanced Technology group were early pioneers in this direction. They pursued the idea of using realistic sounds to inform users about events within the computing environment. Modern computer users are no doubt familiar with the error sounds and trash/recycle bin sounds associated with their operating system.

The pace of development in sonification, which had been relatively slow for quite a few years, began to accelerate near the end of the 1980s. In 1989, Stuart Smith and his team began work on Exvis, which is an auditory/visual display tool for multi-dimensional data. Variables in the data were encoded as geometric features of graphic elements called "icons" and as parameters of synthesized sound [85]. Almost concurrently, Gregory Kramer, of the Santa Fe Institute, began work on sonification of complex systems. Kramer was interested in finding ways for our perceptual systems to contribute to comprehending complexity. In his work, he was attempting to represent 10-dimensional data in an auditory display [58].

Scaletti and Craig, in 1990, developed a series of sonifications to compliment visualizations produced at the national Center for Supercomputing Applications [84]. The resulting sonified data visualizations were used to represent ozone levels, forestry data and swinging pendula. Videos of these visualizations were shown to people in the computer graphics community, which helped broaden the awareness of sonification. The following several years saw progress in this field continuing at electronic game companies, computer and software companies, national laboratories and aerospace and defense companies.

A major milestone in the history of sonification was the first International Conference on Auditory Display in October 1992 in Santa Fe, New Mexico [44]. In fact, the proceedings of this conference, which were broadened into a book by edited by Kramer [57], are where sonification and audification received their names [58]. The conference, with sponsorship from the Santa Fe Institute, marked the first gathering of research devoted to non-speech audio used to convey information. The import of this even was such that one can easily divide the history of the field into what happened before the first ICAD conference, and what happened after. The first meeting consisted of 36 researchers, from fields as diverse as computer science, music, chemistry, mathematics, geology and auditory perception, among many others. The research interests of these individuals were diverse as well: analyzing physical structures, numerical representations of various phenomena, immersive interfaces, etc. It was Gregory Kramer who undertook the time-consuming work of compiling research in this field from across the scientific spectrum and organizing the conference proceedings [58]. Considering the breadth of disciplines represented in this first meeting, it seems fitting that ICAD went on to become a forum for research in all areas that could be loosely tied together with the general description of Auditory Display.

Since that seminal conference, which no doubt helped the development of good research on sonification, some important scientific works and interesting new directions for research have appeared. An in depth investigation of audification as a technique was undertaken by Sandra Pauletto and Andy Hunt [77]. They aimed to understand the general advantages and disadvantages of audification.

In seismology, Chris Hayward was the first to examine the overall potential of audification. He addressed this topic at the first ICAD in 1992 [34]. Other current researchers in this field include Florian Dombois, who established "Auditory Seismology" [24]. Also, in 2008, Meier and Saranti presented some explorations into seismic data using sound [67]. In Physics, Pereverzev et al. used audification to help discover quantum oscillations in HE-3 atoms by listening directly to the data [79]. At the Interactive Sonification workshop in Bielfeld in 2004, Martini et al. used audifiaction to "fish" for atoms [65]. Further applications of audification can be found in the stock market and statistics.

In astronomy, NASA has used audification in recent years, in part as a new way to present their data to the general public. An audification of radio and plasma wave measurements was included in the press materials when the Cassini flew through Saturn's rings in 2004. There is even a web radio or real-time VLF recordings, which is part of the Marshall Space Flight Center's education programs. In astrophysics, sonifications of a variety of data are being published on the web by enthusiasts such as Don Gurnett at the University of Iowa [25].

1.2.4 Sonification and Audification in the Arts

Apart from science, sonification and audification has a rich and varied history in the arts. The 1920s specifically contained much exploration into early electronic music and instruments. Since all electronic instruments use some sort of process that is audified on a loudspeaker, it is by no means a stretch to suggest that the history of electronic music and that of audification are closely aligned. Some well-known examples of instruments developed during this time are the theremin, Ondes Martenot and Trautonium, which were all designed to create microtonal sounds [25]. Music seems to be an obvious application for the sonification of data. Computer music, especially, has seen a large amount of interest in this technique. Some interesting examples include a project called “According to Scripture”, by Paul DeMarini. He was able to turn 19th century visual waveform diagrams, drawn on paper, into sound. “Electrical Walks:, by Christina Kubisch, is a well-know project first shown in 2004. A visitor is given headphones, which audify electromagnetic induction in the visitor’s surroundings. A map with a suggested tour for the visitor is also included [34]. Also in 2004, an Australian group called radioqualia had a piece called “Radio Astronomy” at the Ars Electronic Festival in Linz, Austria. There, VLF recordings from astrological signals sent via network from as far away as Hawaii, could be listened to in real-time. Florian Dombois, the seismologist, has presented audified seismic data at sound installations in Cologne and Berlin [60]. Again at Ars Electronica, Jens Brand from Germany used a topographic model of earth, and satellites acting as the needle of a record player, to audify a cross section of the maps [53]. Further discussion about the creative arts as they relate to the sonification of human EEG signals, is included in a later section.

1.2.5 Sonification of EEG Signals

The focus of this thesis is the sonification of human EEG signals. The literature in this topic is fairly broad in scope, covering everything from the analysis of epileptic brain activity to tangible interaction for the purposes of collaborative musical creation.

There are two ways to access the activity in the human brain with an EEG. One way involves invasive methods involving inserting electrodes directly into the brain. For somewhat obvious reasons such as expense and medical complications, this method is not preferred for sonification purposes. The second method involves noninvasive methods such as the attachment of electrodes to the scalp [56]. Most of the research discussed in this thesis uses noninvasive methods for signal acquisition. Once the signal is acquired, various amounts of processing are usually done. Low pass filtering is a common technique, since the signals of interest are present in low frequency bands [12]. EEG data are particularly well suited to sonification, since they contains multiple time series [40]. However, these signals can be rather noisy, with artifacts from muscle contractions and other unwanted sources [12]. Such signals can be difficult from automatic pattern detection systems to parse. Humans’ highly-developed auditory system, specifically its ability to separate signal from noise, is a great asset and one of the primary arguments supporting the use of sonification across the literature [44]. Some research points to evidence that the human auditory system is based on continuous autocorrelation analysis of audio input rather than Fourier analysis. Autocorrelation can be described as similarity of a signal to itself over time [12].

Parameter Mapping Sonification is a common technique employed in the majority of studies that will be discussed here, and was also utilized in our research. Parameter Mapping Sonification involves the association of auditory parameters with data for the purposes of display. Given the inherent multidimensionality of sound, Parameter Mapping Sonification could be said to be well-suited for sonification of multivariate data. An instructive case study is provided by Grond and Berger in [32]. Consider the simple case of a whistling tea kettle: the kettle produces a particular sound as the water inside approaches its boiling point. It could be said that such a kettle creates much more sound than necessary considering that it merely represents a binary signal (boiling or not boiling). It would be simpler to use an auditory signal that takes a temperature reading from the water and maps it to a sound synthesis parameter, such as pitch. One would be able to listen to the continuous change of the water’s temperature with such a system. However, it is important to note the fact that the sound of a whistling tea kettle is a broadly understood signal, which carries a positive emotional connotation for some. Additionally, the progression from noise to unstable frequency to relatively stable frequency can be said to have a musical quality. Thus, Parameter Mapping Sonification may offer something in the way of efficiency, but there are other important considerations, such as intuitive, emotive and aesthetic issues.

Some early work on the sonification of EEG data was done by Mayer-Kress. Kress used a direct mapping of EEG data into musical pitches [40]. In 1999, Jovanev et al. presented an audification of EEG data [49]. In this case the EEG signals, which again are usually rather noisy, are played without any modification or with only a shift in frequency to put them in a range that is audible to humans. The authors listed some general advantages and disadvantages of auditory data. Advantages include the ability for the human auditory system to process multiple concurrent "streams" of data, even in noisy environments. [44] [49]. Some researchers suggest that the auditory system can deal with levels of complexity far greater than what has been developed so far [44]. Some have argued that these reasons make a strong case for using advanced sonification techniques for multi-variate data such as EEG [40][12]. These are oft-cited advantage, and they tie into the concept of auditory gestalts [41]. Further advantages are faster processing than visual presentation of data, and good temporal resolution. Some disadvantages are limited spatial resolution, the non-independence of some parameters, and the difficulty to precisely quantify certain elements of auditory perception such as loudness. The authors also found some complimentary characteristics of auditory and visual perception, adding that sonification can act as an extension of visualization. In terms of parameters, pitch, timbre and loudness were identified as the most important sound characteristics that can be used in sonification techniques. However, a cacophonous result can easily be reached. In this research, sonification was used to modulate natural sound patterns, as an extension of data visualization [49].

Thomas Hermann has described sonification as a means for aiding in data analysis and the classification of patterns. Hermann et al., in 2002, presented a sonification for EEG data analysis. The data to be sonified in this case was obtained from experiments involving psycholinguistic stimuli, with a goal of analyzing brain activity during high level cognitive processes such as language comprehension. Three different sonification techniques were used: spectral mapping sonification, distance matrix sonification and differential sonification. Spectral Mapping Sonification allows exploration of data by frequency, and provides good results for comparing variations among channels. The STFT of each channel is taken, to increase control of the spectrum. A time-varying oscillator is used to represent the spectrogram of each of the 19 channels of the EEG. Distance Matrix Sonification follows time-variant distance matrices of spectral vectors. In other words, the synchronization of different areas in the brain can be followed over time. Topographical distance between electrodes drives pitch, and the similarity of the signals (calculated with distance matrices) drives amplitude. Difference Sonification allows the comparison of data for one subject to be compared across different experimental conditions. This way, interesting frequency bands and channels can be detected more easily. In this method, the time axis is used to represent location of electrodes. This is considered to be a more abstract sonification [40].

Baier and Hermann [10] characterized dynamic properties of rhythms in some frequency bands of a human EEG. They make the case for using auditory display to investigate rhythmical patterns. Specifically, the introduce a method based on Model-based Sonification (MBS), in which a model acts as the mediator between the data and the sonified output. Model-Based Sonification was comprehensively described by Hermann [35]. The idea is to create a framework to govern how acoustic responses are generated from the actions of a user, and how these observations can be used in data sonification. MBS requires the creation of processes that systematically involve data and are capable of evolving with time to generate acoustic signals. Their precise definition for MBS is as follows:

"Model-Based Sonification is defined as the general term for all concrete sonification techniques that make use of dynamic models which mathematically describe the evolution of a system in time, parameterize and configure them during initialization with the available data and offer interaction/excitation modes to the user as the interface to actively query sonic responses which depend systematically upon the temporal evolution model."

In this case of Baier and Hermann's study, the model is a set of differential equations, and the data is used for feeding the model. The dynamic behavior is determined by an independent time variable (called sonification time) and by data-dependent interactions. In this sense, the model has a 'mind-of-its-own' and simulates the behavior of a real-world acoustic system. Temporal and spectral information are sonified using this model. The temporal information reveals something about the phase of underlying EEG rhythms. The relationship between this and following wave helps define a temporal ordering, which can be extracted and made audible. With regard to the spectral information, absolute frequency is not of interest in this context. Rather, relative frequencies are used to describe values of the scaling factor output by the model in response to a sine wave perturbation.

In [15], Baier et al make the case for why sonification of EEG is a good method for investigating relationships with regards to rhythm. Epileptic seizures can be described as order/disorder transition in the EEG. This results in a change in the degree of synchronization of firing among neurons both close together and far apart. The displayed EEG data in this case will show differences in temporal autocorrelations and spatial cross-correlations. Evidence that sonifications can detect autocorrelations and cross correlations was provided by Baier et al. [15]. Other previous work by Baier in [14] concluded that sonifications are a good way to investigate if psychological rhythms are deterministic or stochastic. In [12] it is argued specifically that event-based sonification can be used for rhythm detection. In terms of mappings for [11], minima and maxima for each channel in the time domain were considered to be 'events'. Each maximum triggers that playing of a sound from a predefined synthesizer in SuperCollider [supercollider site], a software platform for real-time sound synthesis. The volume of the triggered sound is determined by the voltage difference between present maximum and previous maximum. Duration of the triggered sound is modulated by inter-maxima interval (period between present and previous maxima). Utilizing a reciprocal mapping, the number of harmonics is controlled by the period between maxima in one time series and previous maxima of another time series. Although this study was conducted offline, the authors see the benefits of real-time parameter control.

Baier et al, soon followed with a real-time application of event-based sonification of EEG rhythms [10]. The presented system suppressed irregular background irregular background in the signal and highlighted normal brain activity. The authors contend, along similar lines as in [11], that simple audification does not allow proper discrimination of rhythmic features from background noise, and so sonification becomes a more appropriate technique. Event-based sonifications can be easily implemented for real-time applications. This allows the direct detection temporal relationships in the data if the mean period between two events falls within the range in which the human ear best processes rhythms. The mappings presented here again use SuperCollider for synthesis. The maxima of each channel triggers the playing of a pre-defined Supercollider sound. The volume of the event is a linear mapping of the voltage difference between present maximum and previous maximum in the same time series. Duration of the played tone is modulated by the inter-maxima interval, as is the number of harmonics. The authors identify the property of sound perception to convey information about space, and that this had yet to be exploited in data sonification.

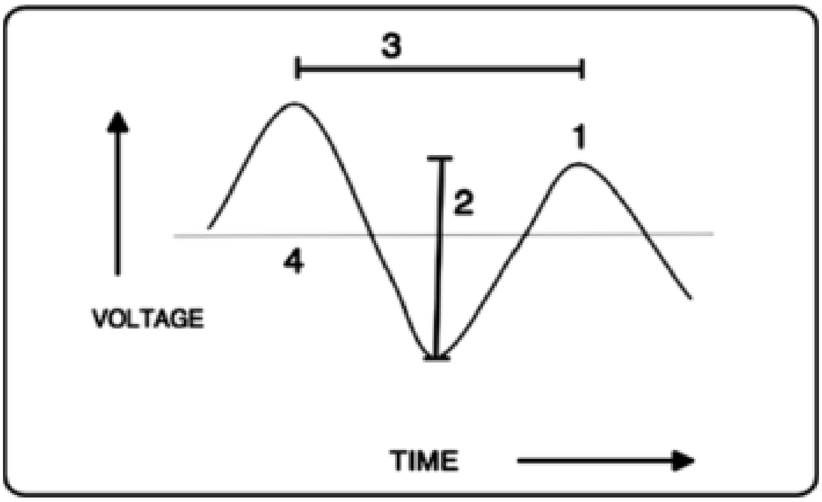


Figure 4: Parameters for sonification in [11]. 1: voltage maximum; 2: voltage difference between present maximum and previous minimum; 3: time difference between present and previous minimum; 4: threshold voltage.

This work was followed by another real-time event-based sonification technique described in [13]. A multi-channel sonification is presented, including the perception of spatial characteristics of the data. A multi-speaker environment is used. The mappings are similar in most respects to [12], with the addition of the spatial arrangement of the output being arranged around a coordinate system based on the 20-10 system. The x-axis of this arrangement is the ear-to-ear axis of the electrode layout, and the y-axis is the taken from the neck-to-nose axis. They used an 8-speaker setup, designed so that the listener's attention would be directed in the appropriate angle depending on its location in the described coordinate system. In terms of mapping, amplitude of the sonification is mapped to energy within a spectral band. Frequency is controlled by spectral band center frequencies. Pitch is also used to represent activation variations. Band activations are mapped to pitch deviations from the center pitch. A left/right hemisphere to left/right stereo channel mapping is also performed.

Meinicke et al used spectral mapping sonification to aid in the identification of discriminative features in EEG signals [68]. Specifically, the authors were looking for which electrodes and frequency bands are responsible for stimuli-specific differences in EEG data. Using more or less typical processing, they band-bass filtered the signals (0.3Hz to 35Hz), and digitized them using 16-bit quantization and a sampling rate of 256Hz. Extraction of features required applying the Short Time Fourier Transform to the signal, using a window length of 1 second and an overlap amount of 50%. Spectral amplitudes were averaged over the ranges of six frequency bands.

1.2.6 Brain-computer Interfaces

Brain-computer interfaces (BCIs) translate brain activity into signals controlling external devices [19]. Such devices can allow direct brain communication in patients who are completely paralyzed, or restore movement to limbs via the transmission of brain signals to external prostheses. It is important to differentiate invasive BCIs, which employ electrodes implanted into brain, from non-invasive BCIs, which use sensors outside of body boundaries to detect signals. For non-invasive BCIs, acquirable types of signals include slow cortical potentials (SCP) of the EEG, sensorimotor rhythms (SMR), also called mu-rhythms and P300 and other event-related potentials [19]. The first work towards communicating with a computer using EEG can be traced to the work of J. Vidal, in 1973 [92]. Some early groundbreaking work in BCIs was conducted by Wolpaw [97]. Birbaumer et al used Slow Cortical Potentials as a BCI input signal [20][63]. Some neurological disorders can lead to a degree of vision loss, so the concept of an auditory BCI is attractive [74]. Sellers and Donchin, in 2006, tested a four-choice P-300 BCI on patients afflicted with ALS. Patients were presented, either visually, auditorily or both, with the word “yes”, “no”, “pass” and “end”. The subjects were asked to focus attention on either “yes” or “no”. The authors found that this 25% target probability was good enough for a stable P300 response during a period of 12 sessions, in both ALS patients and healthy individuals. Further support for the idea of an auditory BCI comes from Hill et al., in a 2005 paper. P300 responses evoked by two simultaneous auditory stimuli were classified. Subjects were directed to focus on one of the two streams. Results indicated that it is possible for users to consciously modulate event-related potentials in response to auditory stimulus [42].

In 2002, Hinterberger et al presented a paper describing the Thought-Translation-Device (TTD) [46], a BCI device that allows communication for completely paralyzed patients using only brain signals. The study involved self-regulation of slow cortical potentials achieved through feedback training. Further discussion of biofeedback and neurofeedback can be found in the following section. In terms of auditory feedback, the SCP shifts are mapped to pitch in a MIDI voice. High pitch indicates cortical negativity, and low pitch indicates cortical positivity. The authors conclude that self-regulation can be taught with an auditory display.

Hinterberger, in a 2004 paper, presented “Poser” or Parametric Orchestra Sonification of EEG in Real-Time for the Self-Regulation of Brain States [44]. This was an extension of the previously presented Thought-Translation Device. Previous work with self-regulation of EEG (specifically with Slow Cortical Potentials) involved a spelling device for paralyzed patients [18]. In previous work, Hinterberger conducted a comparison of visual and auditory feedback for Slow Cortical Potentials self-regulation found that a simple pitch assignment sonification did not improve results for subjects. Also, a combined auditory and visual feedback was found to have less significant results than either of the two elements taken alone [46]. Hinterberger points out that auditory display uses artificial sounds, so all parameters associated with that sound are under human control. This arrangement allows the use of countless different parameter mappings (control of pitch, duration,etc) [58]. Additionally, human performance depending on simultaneous input from multiple sources has been shown to be significantly better with auditory display compared to a mixed audio and visual display, or a visual display alone [58].

In POSER, EEG data is organized into frequency bands, and extrema in a frequency range below 12 Hz are sonified by triggering a note at each wave maximum. Differences in potential are calculated for adjacent extrema (maxima-minima or minima-maxima) are also computed. Peak-to-peak times are converted into frequency for pitch modulation. These extracted parameters are then assigned to voices in a MIDI device. Decomposition of the EEG signal into frequency bands due to different origins of components, and parameters associated with each band can be extracted. The results from this work suggest that self-regulation of EEG signals is possible with orchestral feedback [46].

1.2.7 Biofeedback/Neurofeedback

The term ‘biofeedback’ is defined by Rosenboom as “the presentation to an organism, through sensory input channels, of information about the state and/or course of change of a biological process in that organism, for the purpose of achieving some measure of regulation or performance control over that process, or simply for the purpose of internal exploration and enhanced self-awareness” [82]. Usually, this presented information will be of a type that is not accessible to that organism. Similarly but more narrowly, Neurofeedback can be defined as a method used for self-regulation of physiological, especially neurophysiological, body signals [43]. Neal Miller, in the 1960s and 70s conducted pioneering research into the modalities of self-control, suggesting the the human autonomic nervous system might be susceptible to voluntary control and training [82].

In October of 1969 the Biofeedback Research Society was formed and held its first meeting in Santa Monica, California. At that meeting, the technique of biofeedback officially was given its name [30]. Neurofeedback started to become noticeably popular in the 1970s around the time when some early training devices were becoming available. Self-regulation training is usually administered using visual, acoustical, or mixed display of a physiological signal, such as EEG. EEG feedback became popular after the publication of studies by Kamiya concerning the connection of alpha wave amplitude and relaxation [52]. Unfortunately, a clear connection between them could not be maintained under further scientific study. EEG neurofeedback has been used for therapy in patients with epilepsy [88]. Birbaumer’s research demonstrated human self-regulation of SCPs below 1 Hz [20][63]. Current applications of neurofeedback include the treatment of attention deficit and hyperactivity disorders in children [62].

Neurofeedback has also been used in conjunction with BCIs for training of direct brain-computer control by using self-regulation of brain signals. With training, a BCI can classify brain activity in terms of intentional meaning. In past studies, users were able to learn regulation of slow potentials so that the BCI could discriminate between a positive and negative response [45][51]. Mu rhythm regulation was demonstrated in a study using imagination of a hand gesture which was detectable by a classification algorithm [88]. As a hypothesis for the underlying mechanisms that might explain successful neurofeedback, Hinterberger posits that neurofeedback closely connects the patient’s physiology with his or her consciousness. Perhaps this improves body awareness, and the relationship between self and body. The strengthening of this bond might help facilitate necessary changes or improvements in symptoms or behavior [43].

In 2010, the ‘Sensorium’ was presented, also by Hinterberger. This system can be described as a neurofeedback environment which allows subjects to experience signals from their imperceptible body processes both visually and auditorially. While this system is based in part on previous work involving the Thought-Translation Device, the sonification portion of the software was reprogrammed for this purpose, with the new system and algorithm now being called SymPOSER. The SymPOSER software consists of three basic processing classes: a filter class, a MIDI control class and a light control class. The filter class contains two selectable types of filters, a Finite Impulse Response band pass filter, and an Infinite Impulse Response filter that can be configured as a band pass, high pass or low pass. These filters can be used for the separation of EEG signal into its usual frequency bands. Once filtered, the data can be sent directly to the output, or be subjected to further processing: band power calculation, extrema detection (for triggering event sounds) and the conversion of the time between two extremes into frequency. Thus, there are four outputs of a filter class, any one of which can modulate the pitch, velocity, touch and amplitude of a MIDI note in the next base class [43].

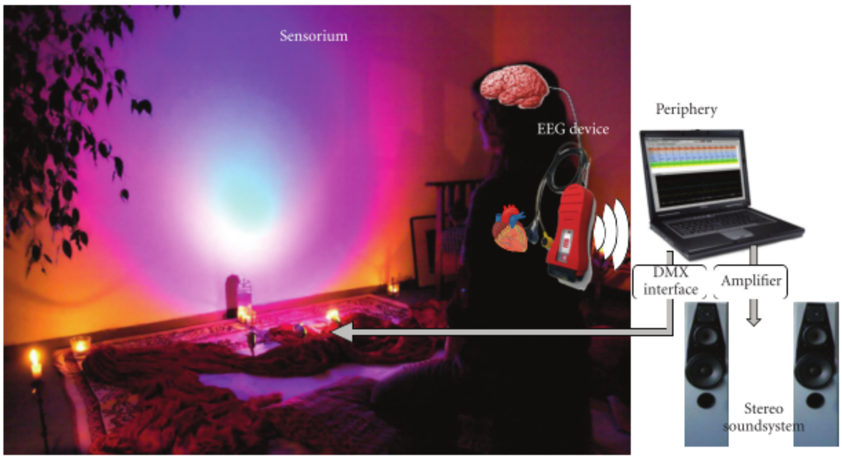


Figure 5: Experimental setting used to test the Sensorium, in which subjects listened to and watched their own body signals.

Nijboer et al. used an auditory BCI to train subjects to affect the amplitude of sensorimotor rhythms of their EEG signal [74]. One group of subjects was given auditory feedback and a second group was given visual feedback. The overall performance was superior for the visual feedback group, but by the end of the third training session, there was little to no difference in performance for auditory versus visual feedback. This suggests that with sufficient training time, auditory BCI can be as efficient at visual BCI. In the study, harp or bongo sounds were used for feedback, depending on synchronization levels. The level of synchronization/desynchronization was mapped to the amplitude of the feedback sound.

Kogure et al analyzed event-related potentials evoked by auditory stimuli as they relate to BCI [56]. Subjects were asked to determine the direction of origin for a given sound cue. The results indicate that it may be possible to develop a BCI that can estimate the direction of a sound.

An attempt to create a BCI based on ‘inner tones’ and ‘inner music’, or the tones and music imagined but not sung aloud, is presented in [55].

1.2.8 BCI/EEG/Music Composition

Music is a powerful human communication tool that has been used across time and cultures. It can also be used for emotion and mood modulation [78]. Throughout the past 50 years, a number of artists and scientists have harnessed the power of the human brain for the purposes of composing or performing music. Indeed, artists are always ready to experiment with scientific and technological breakthroughs for creative ends [82]. Still, it is believed by some that BCI systems have yet to show their full potential in terms of musical applications [33]. As mentioned above, the earliest attempt to hear brainwaves as audio, as previously mentioned, was Adrian and Matthews in 1934. Alvin Lucier's "Music for Solo Performer" appeared in 1965, and involved a direct mapping of the performer's alpha rhythms onto a group of percussion instruments [82]. Rosenboom developed a participation/performance event called *Ecology of the Skin* in 1970-71. This involved biofeedback and musical translation of brainwaves as well as heart signals from performers and audience. Teitelbaum's *T'ai Chi Appha Tala*, involved the transmission of alpha signals from an artist while engaged in the practice of T'ai chi Chi'an. These signals were transmitted by a brainwave amplifier and FM transmitter attached to the artist herself. Teitelbaum also created a piece called *Spaceship* in which EEG and other body signals were used as control sources for synthesizers [8]. Before the 1990s most similar attempts used alpha wave amplitude or other simple and direct parameter to drive the composition. In 1997, Rosenboom presented a system using new music generating rules based on digital filtering or coherent analysis of the EEG signal [99].

Wu et al, present a method of turning human EEG signals into music, with a goal of representing mental states through music. Arousal levels of mental state and music emotion are used to create compositions. Arousal levels are based on EEG features that are extracted using wavelet analysis. Music emotion is related to parameters such as pitch, tempo, rhythm, etc. After the extraction of the EEG signal features, musical segments based on the extracted features are defined. Next, bars of music are generated, and notes are fixed based on bar parameters. Finally, the melody is constructed using MAX/MSP [2], and a MIDI file is generated. Their results suggest that mental states can be identified by listening to the corresponding music composed using the system. The authors also note the importance of finding a balance between the science of direct translation of the EEG and the are of composition sought for composing music with brainwaves[98].

In a similar paper, Wu et al. presented a mapping of EEG waveform amplitude to pitch based on the scale-free phenomenon. The change of EEG energy was mapped to note volume and the period of EEG signal was mapped to the duration of notes. For testing, some EEG segments were translated into music and evaluated by listeners [99]. Hamadicharef et al also used a BCI for musical composition, allowing the user to select notes, rest, delete or play in the creation of short melodies. These selections are made using P300 features [33].

Miranda et al. present a system, called the Brain Computer Musical Interface-Piano, that uses brainwaves to compose music in real-time. Whereas the other BCI music applications discussed here rely on the user's ability to control specific aspects of their EEG, here the authors have developed a system that interprets the meaning of the user's EEG instead of being explicitly controlled by the user. Still, the authors acknowledge the possibility of biofeedback with their system. The BCMI-Piano is programmed to search for information within the EEG signal and match what it finds to various generative musical processes in different musical styles. In terms of sonification, spectral information in the EEG is used to activate the generative music rules, and the complexity of the signal is used to control the tempo of the music [70].

Miranda et al. introduce Music Neurotechnology as an emerging interdisciplinary research area existing at the intersection of Neurobiology, Engineering Sciences and Music [71]. Research into BCIs to control music systems would fall under this definition [72]. Also introduced is neurogranular sampling, which is a sound synthesis method based on spiking neural networks (SNN) to control the triggering of sound grains from a certain sampled output. The neurogranular sampler has since been used to contribute to artistic works including the sound elements in a sound and video installation, and an award-winning piece involving real-time simulated versions of the instrument distributed around 24 different sites in the UK [71].

Other recent examples of BCI music systems include Grierson et al., who presented a computer music device controlled by detected P300 events [31]; In [8], the authors propose a system for analyzing electromyogram (EMG), electrocardiogram (ECG) and electro-oculogram (EOG) in addition to EEG to control sound synthesis algorithms; Swift et al. have devised a system to used the “natural” brain activity of musicians to shape and modulate music in real-time as it is being composed and played [89].

1.2.9 Interactive Sonification

Hermann and Hunt have devoted attention to the use of human interaction in sonification applications. They define Interactive Sonification as “the discipline of data exploration by interactively manipulating the data’s transformation into sound.” They argue that human perceptual acuity is tuned to a combined audio-visual (often tactile and olfactory as well) experience that changes instantaneously over time as we perform different actions. Understanding these different elements and how they interact can help us learn the best methods for presenting data and building interfaces for human-computer interaction [34].

Hermann et al, presented an interactive tangible computing system for controlling data sonifications both in real-time and offline [39]. As discussed, interactive sonification is concerned with the interaction loop between user and sonification system. The authors approach here is to use tangible objects to establish a highly controllable interaction loop. Tangible computing involves the representation by physical objects of various data features, and the orientation of the objects and the distance between them can be used to manipulate how different data channels contribute to the overall sonification. In contrast to a more traditional GUI, which allows only a limited amount of interactands (such as a mouse pointer), or a mixing board interface, in which the spatial organization is somewhat fixed, tangible systems can offer a higher degree of control dimensionality.

Furthermore, standard exploratory analysis of multivariate data (such as EEG) utilizes a stacked function (probably show typical EEG plot here). While this may be sufficient for a global view of the data, it is perhaps less well suited for quick detection of fluctuations or phase shifts between channels. In terms of display, we see that multivariate data have interesting features that are difficult to display in one real-time visualization. Sonification, in this case, can act as an extension and complement to visual displays without interfering with visual analysis, not to mention the frequentlycited streaming capabilities of our auditory system. Here, the tangible objects include channel objects, sonification objects and selector objects. The ID of the objects, in addition to their location and orientation on the interactive surface is acquired using a tracking system based on fiducial markers [16] and sent using the TUIO protocol [51] to the sonification system. For sonification, two straight-forward approaches are presented: multi-stream audification and multi-stream sonification. The audification technique involves windowed pitch shifting using granular synthesis, while continuous parameter mapping is used in the alternative technique. The authors note the potential for further work in tangible computing and interaction, since acoustic responses that are coupled to the manipulation of physical objects can strengthen the perceived relationship between the object and its meaning within the sonification system.

More recently, Mealla et al have explored the effects of interactive sonification in collaborative musical performance [66]. They presented a multi-modal system, using physiological signals and the ReacTable [48], which is a musical tabletop interface for real-time sound generation and control. This system displays users' physiological signals through sound, graphics and tangible objects, called physiopucks. The Pure Data software platform is utilized here for audio synthesis. The authors' hypothesis is that the use of physiological signals will enhance important aspects of music creation in collaborative scenarios.

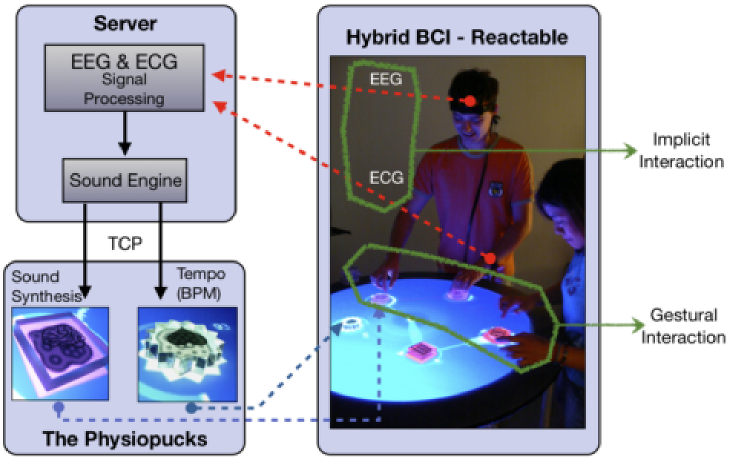


Figure 6: The Multimodal Music system as described in [66].

2 System Development

In this chapter, the sonification system will be described in detail. Signal acquisition and processing will be discussed, followed by the development of the sonification strategies and mappings used in our research.

2.1 Preliminary Considerations

In terms of system design, some technological requirements needed to be satisfied. Since our research deals with real-time sonification, it was of the upmost importance that the processing time for the entire signal chain-from signal acquisition to sonification-be minimized. Additionally, the reading and processing of data within the system needed to be done at a constant rate. The device selected for signal acquisition was the Emotiv EPOC wireless neuroheadset [3]. This device is a wireless interface for the acquisition and processing of human EEG signals. It contains 14 electrodes meant to be placed directly on the scalp. The EPOC was chosen for its power, flexibility and the strong community of developers and researchers who have adapted the device for a variety of different purposes. The overall technical considerations necessitated dividing of the overall system into two subsystems. Two Apple MacBook Pro laptop computers with very similar hardware specifications would each handle specific parts of the process, to avoid one machine becoming overloaded or sluggish during sonification. In the end, this proved to be a wise decision, since our overall system consisted of multiple operating systems and various types of software.

One computer handled the signal acquisition and processing part of the system. This computer utilized the following software to achieve these tasks:

- OpenVibe Acquisition Server
- OpenVibe Designer Environment
- VRPN to OSC conversion software
- Pure Data

The second computer was responsible for the sonification part of the system. This computer was running:

- Pure Data
- Ableton Live

2.2 Physiological Signal Acquisition and Processing

In the simplest terms, our system was required to be able to extract certain EEG features and perform some signal processing on the extracted data.

As a first simple step, we considered using the TestBench software that is bundled with the Emotiv EPOC device. However, the software uses proprietary filters and processing techniques to which we did not have access. Although the TestBench software can display the level of ‘meditation’ of the user, without knowing how this value was calculated or how the signal was treated beforehand, we could not use it to build our system or conduct our tests. Additionally, streaming data from this software to the sonification portion of the system was not possible without additional software. Intermediary software known as Mind Your OSCs exists for the purpose of transmitting the Test Bench values as OSC messages. While this is certainly useful for sending data from the Emotiv to other software such as Pure Data, it does not solve the issue of lack of access to the raw data. For these important reasons, TestBench was quickly abandoned.

EEGLAB[5]], an EEG processing toolbox for Matlab, was considered next. Unfortunately, this software failed to meet our requirements for real-time signal processing and streaming. It has some powerful capabilities for signal evaluation in general, but for our specific purpose of sonifying signals in real time in addition to analyzing them, it was not the best choice.

Finally, a suitable mixture of processing speed and features was found in OpenVibe, which is a software platform designed to design, test and use Brain-Computer Interfaces [6]. OpenVibe was chosen for a number of reasons. Firstly, it's relatively simple graphical interface made designing and configuring custom systems fairly simple. OpenVibe includes a proprietary acquisition server which can extract raw data from the Emotiv headset at constant high speeds of up to 128 samples/second. Additionally, the on-screen visualization of the data in real time was quite helpful for testing the system and running the experiments. Lastly, due to OpenVibe's integrated communication capabilities to other software using theVirtual Reality Peripheral Network (VRPN) protocol, sending the data to the next step in the system chain was relatively straightforward.

In order to have access to the numeric data, an intermediary client/server was required to repack the VRPN data as OSC messages so that software such as Pure Data could understand them properly. A piece of software called vrpn2osc.exe [91], written specifically for sending data from OpenVibe to OSC clients, was used.

2.3 System Architecture

This section describes the design of the system used to acquire, process and sonify the EEG signals from subjects. As described previously, the system has been divided into two subsystems, each one running on a laptop computer of similar specifications. A detailed graphical illustration of the complete system is provided below.

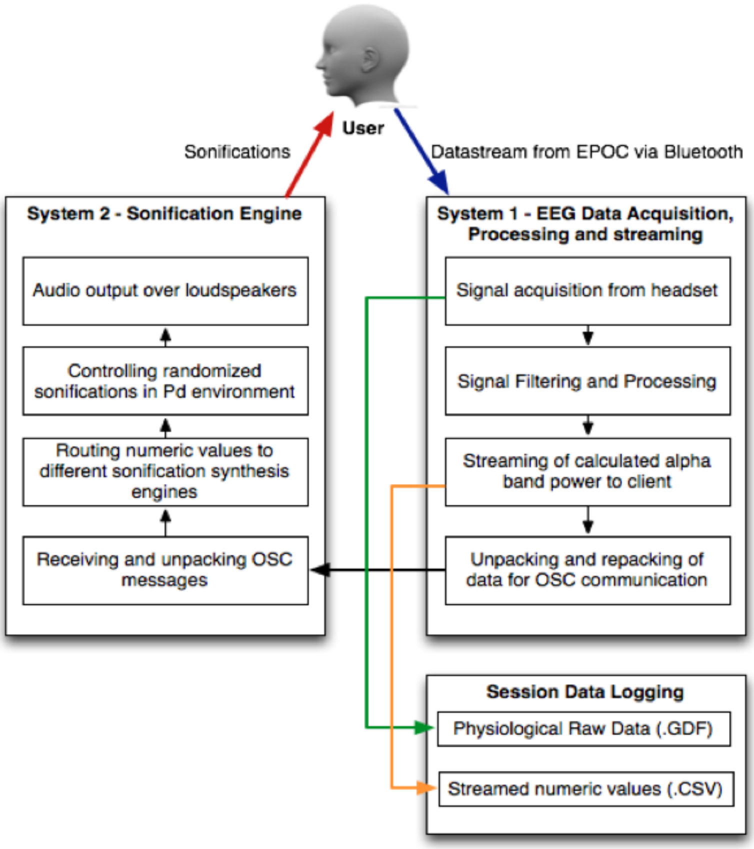


Figure 7: Graphical overview of system architecture

2.3.1 Signal Acquisition and Digital Signal Processing

The Emotiv EPOC consists of 14 saline electrode sensors, and so the complete stream of data received from the device consists of 14 separate channels. For our purposes, this stream was effectively reduced to 6 channels (O1, O2, P7, P8, T7, T8), those associated with the temporal, occipital and parietal lobes. These channels are useful for displaying alpha band activity and they not as susceptible to artifacts caused by facial muscle contractions. Through the signal processing scheme described below, the effective band power of the alpha range is calculated. This allows us to quantify, in an objective way, the amount of relaxation exhibited by the data.

The flowchart below illustrates the signal flow:

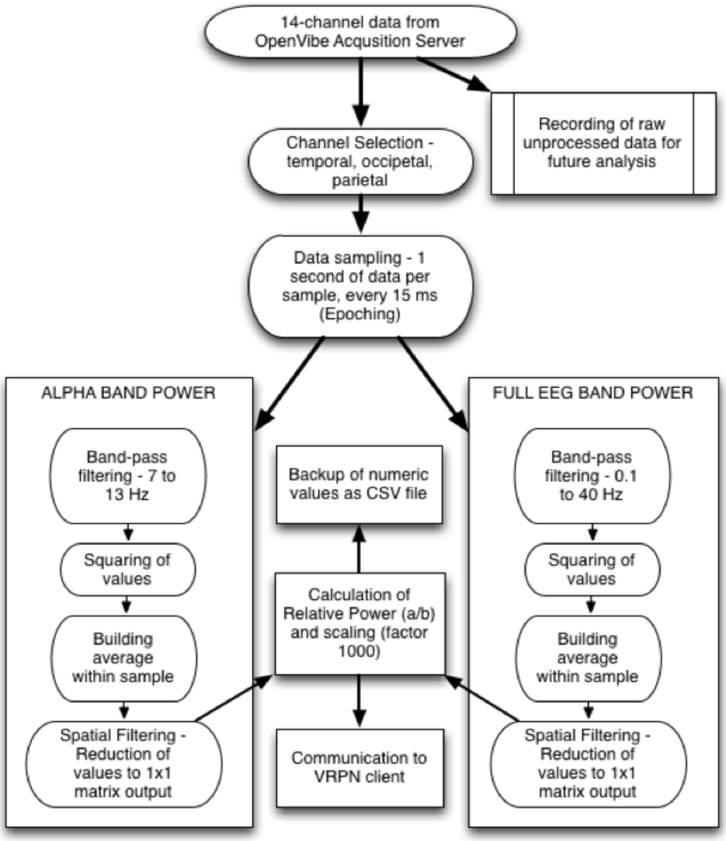


Figure 8: Flowchart illustrating signal acquisition and processing

The patch designed in the OpenVibe environment is shown below. It corresponds with the Figure 8:

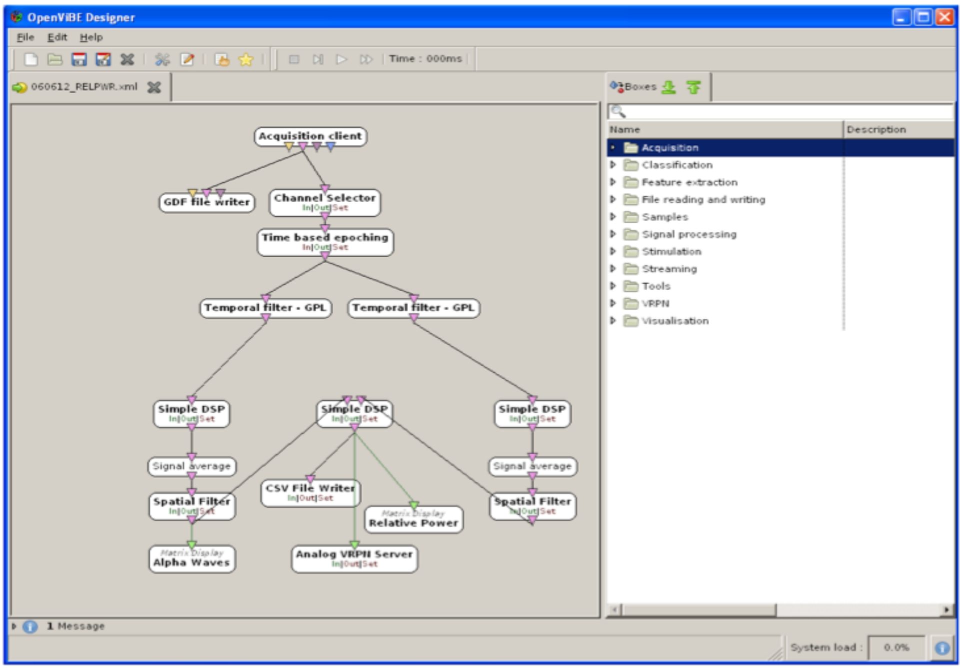


Figure 9: OpenVibe patch for signal acquisition and processing

An explanation of each component of the OpenVibe processing patch follows:

1. **Acquisition Client -** establishes communication with the Emotiv EPOC device.
2. **GDF File Writer -** Records oscillatory data as a GDF file, which can later be opened and processed within OpenVibe. This allows us to save raw data for physiological evaluation.
3. **Channel Selector -** Allows the user to select or discard specific channels from further processing. We chose channels O1, O2, P7, P8, T7, T8, where the alpha amplitudes are more pronounced and muscle artifacts of reduced consequence.
4. **Time-based epoching -** The time-based epoching box generates 'epochs', i.e. signal 'slices' whose length is configurable, as is the time offset between two consecutive epochs. This box has one input and one output connector, both of which are of 'signal' type. This box is essential to other signal processing boxes when the size of data blocks being forwarded to them is not significant enough.
5. **Temporal filter -** This is a digital filter module allowing for high-pass, low-pass, band-pass and band-stop filtering of frequency information. We used 4th order Butterworth filters to isolate the alpha band (7-13 Hz) and in the second stream, the full EEG bandwidth (0.1 - 40 Hz).
6. **Simple DSP -** This box allows the user to enter mathematical operators to process the signal. In our system, we used simple signal squaring to turn negative amplitudes positive.
7. **Signal average -** This plugin computes the average of each incoming sample buffer and outputs the resulting signal. The output signal's sample count per channel per buffer is one, since a buffer contains the averages (per channel) of the values of an input buffer.
8. **Spatial filter -** The spatial filter generates a number of output channels from another number of input channels, each output channel being a linear combination of the input channels. e.g. if IC*j* is the *j*th input channel, OC*k* is the *k*th output channel, and S*jk* is the coefficient for the *j*th input channel and *k*th output channel in the Spatial filter matrix, then the output channels are computed as:

   OC*k* = Sum on *j* (S*jk* * IC*j*)

   The spatial filter in our example is set to compute a single value from the six incoming input channels.
9. **Matrix Display -** Outputs the incoming 1x1 numeric value to a display on the screen.
10. **CSV File writer -** Saves incoming data to a CSV file for posterity.
11. **Analog VRPN Server -** Streams the incoming data to a client using the VRPN protocol (Virtual Reality Peripheral Network).
12. The second **Simple DSP** box divides the alpha band power by the power of the full EEG spectrum, giving us the relative power of the alpha band. This helps to address inconsistencies from subject to subject, and also attenuate the effect of motion artifacts to some extent.

2.3.2 Data Packing and Communication

Communication from OpenVibe to the packing module is established using a piece of software that acts as a VRPN client and outputs OpenSoundControl (OSC) messages in real time. This software is designed to read from the VRPN server within OpenVibe called *vrpn_analog_openvibe* and can receive two data streams simultaneously. The data it receives are then repackaged as OSC messages and sent to port 12345 on the host machine. The data is then received by Pure Data, which is running on the same system as the OpenVibe software. After receiving messages from port 12345, it divides the stream into two discrete OSC channels entitled /alpha and /ampli, the second of which is not currently used but is retained for future purposes.

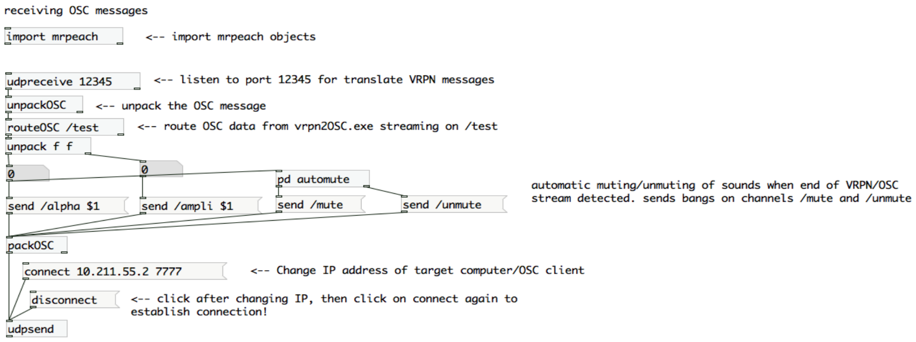


Figure 10: Patch within Pure Data for receiving and repacking OSC messages.

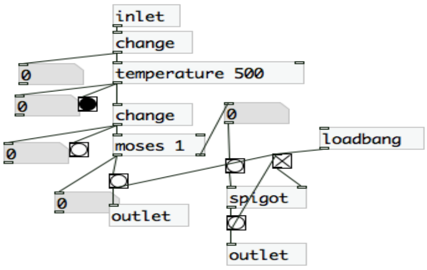


Figure 11: Mute/Unmute patch in Pure Data

Furthermore, to maintain consistency between start and end times of physiological recordings, there is a muting and unmuting function built into the patch as the sub-patch entitled “automute”.

The automute patch essentially detects the number of changes in the incoming OSC values within a specified period of time (500 ms in our implementation). When the supervisor presses the stop button within the OpenVibe scenario, the number of changes in value drops to zero and the automute sub-patch sends a “bang” message to the OSC channel /mute. When the play button is pressed in OpenVibe, the patch begins to receive changing values again and sends a bang message to OSC channel /unmute. These channels control the output of the DAC within the sonification engine.

2.4 Sonification Engine

It was decided early on in this research that the Pure Data programming language would be used to build the sonification engine. Pure Data is described as a “real-time graphical programming environment for audio, video and graphical processing.” It was originally developed by Miller Puckette and company at IRCAM, and Puckette himself writes and maintains the core of the language[100] . Importantly, Pure Data (commonly called Pd) has been extended over the years by a dedicated and diverse group of developers, who have contributed additional libraries and functionality to Pd. Previous research work has been conducted in the field of sonification using this software [66] [101]. The open-source nature of Pd and the supportive online community of users and developers were important features during the research for this thesis. Compared to some other programming languages, Pd's relative ease of use and real time graphical interface were advantages during both the system development and the experiments.

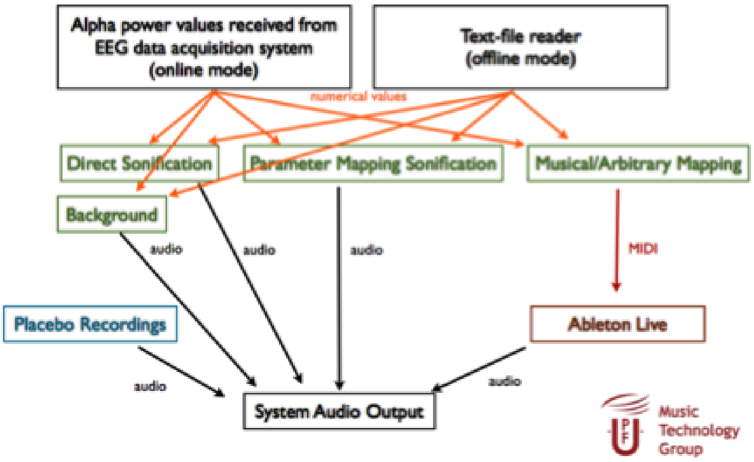


Figure 12: Overview of Sonification Engine

2.4.1 Data Transmission and Routing

In figure 7, we see that the subsystem containing the sonification engine is receiving data from the subsystem containing the EEG signal acquisition and processing functions. The sonification engine must first receive the data sent from the other computer, and then route the data properly so that they can be sonified. The receipt and routing of incoming data are handled by a subpatch called 'pd acquire_signal'. An image of this subpatch is below:

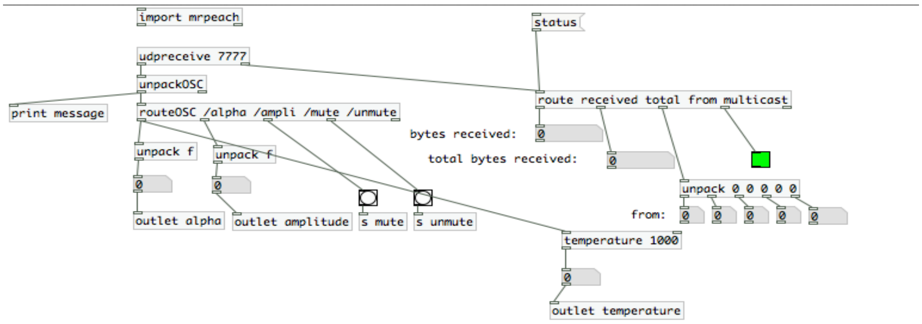


Figure 13: Sonification engine subpatch responsible for acquiring data from the other subsystem

Once the data is received within Pd, it is then sent simultaneously to three other subpatches, which control the sonification strategies that will be discussed in detail in the following section. It is important to note here that in addition to a real-time sonification of incoming data (what can be called 'online mode'), a second mode (that we will call "offline mode") is also built into the system. Significant amounts of the development and testing of the sonification engine and various sonification techniques was done when the system was not fully constructed or functioning. For offline testing the system has the ability to read prerecorded text files, at a rate equal to that of real-time streaming. This functionality allowed us to sonify data without necessarily needing a real-time stream coming from the EEG headset.

To select which sonification strategy is to be heard, the user adjusts the volume slider for the desired strategy on the main panel of the user interface, making sure that the other techniques remain at 0.

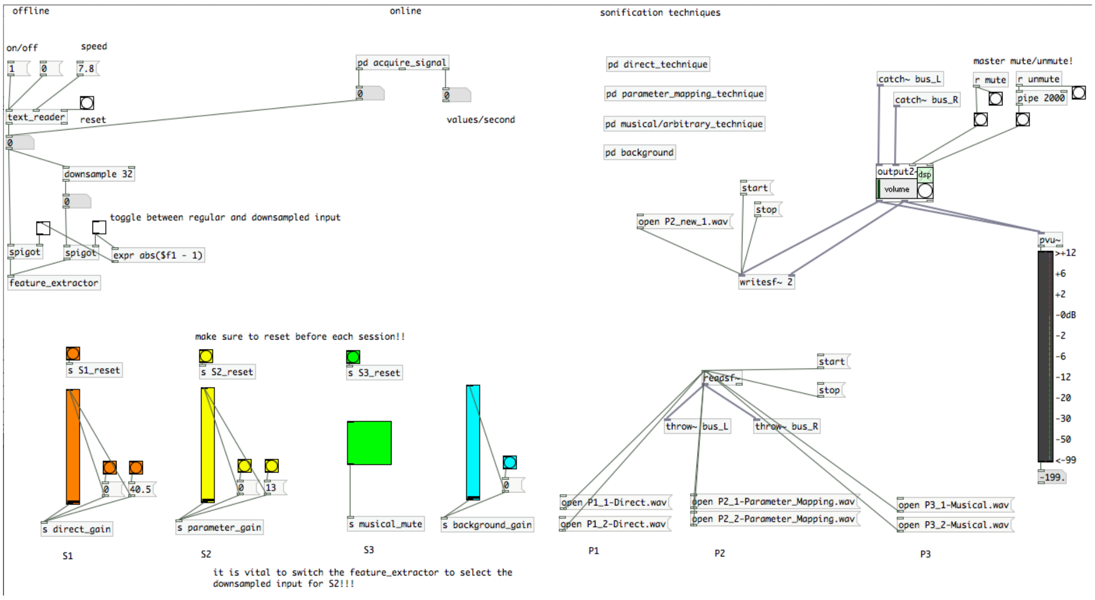


Figure 14: Main panel of the sonification engine, including sliders for adjusting the volume of each sonification technique.

2.4.2 Sonification Strategies

In this research, we have attempted to answer questions concerning what type of sonification strategy or mapping is best in order for a subject to coherently perceive an audio input as being representative of his or her internal brain states. As we have seen, many studies have been published involving the sonification of EEG signals [cite, cite, cite], but most of this research focuses on only one sonification strategy. In order to compare different strategies and reach some conclusion about which type is best for our purposes, it was necessary to develop a system capable of producing multiple types of sonifications. These sonification strategies, of which there are three, range from relatively simple (from a signal processing and mapping standpoint) to more complex or arbitrary.

2.4.2.1 Direct Sonification/Audification

As described in the previous chapter, the simplest strategy for sonification is called audification, and it typically involves the direct translation of data into sound. Other than a frequency shift to make the data audible, as was necessary in Speeth's research into the sonification of seismic data, no other processing may be done if a technique is to considered audification [87]. Audification was seen as the natural starting point for the most simple or direct sonification strategy in this research.

With the simplest possible strategy in mind, it seemed that mapping the received values to the frequency of an oscillator within Pd could be an option. However, as we would later learn, the data streamed from the acquisition portion of the system tended to have values that were quite low, generally less than 100, and so a frequency shift was necessary to make this strategy produce a completely audible sound. Although a working prototype of this strategy was arrived at rather quickly, we decided that the mapping was in fact too simple, and merely produced a sine wave of variable frequency. While we were certainly adhering to the guidelines for audification, a slightly more flexible approach was desired.

After testing some other basic techniques, we settled upon FM modulation synthesis [23] as the synthesis method for the most basic sonification strategy. FM synthesis is fairly simple from a signal processing standpoint, but it can result in some complex, harmonically-rich waveforms. Simple FM synthesis works on the principle that one signal (called the "carrier") is modulated by a second signal (called the "modulator"). The amount of alteration in the resulting signal is dependent on the amplitude of the modulator.

Complex FM synthesis involves the addition of at least one more carrier or modulator. For example, one modulator can affect two carriers, or multiple modulators, arranged in parallel or chained together, can modulate a single carrier.

For the sake of synthesizing a sound that was not terribly unpleasant to listen to, we decided to choose a simple FM technique with one carrier and one modulator. Since only one stream of values was being provided by the signal acquisition system, we had to choose which of the signals would be affected by the incoming stream of data, and how to make the resultant signal audible. We ultimately decided to have the input data affect both the carrier frequency and the modulator, but in different ways. Rather than immediately scale the input values to an audible range, we instead subtracted them from a fixed initial value of 450 Hz. In this way a higher input value would yield a lower carrier frequency. This was done to avoid a situation in which a higher input value, which we have associated with a higher amount of the subject's state of relaxation, with a higher pitch sound, which could be subjectively annoying. The mean of the input signal was calculated in real time and used as the frequency for the modulator signal. The "depth" or amount of amplitude given to the modulator signal was set and left at 10 throughout our tests and experiments. This provided enough of the modulator signal to create some harmonic richness, but not too much to create an uncomfortable listening experience. Furthermore, it was felt that rapidly changing the depth amount by tying it to the input value in some way was unwise, again because of potentially uncomfortable sounds. The sonification that resulted from these techniques was a dynamic rapidly-changing modulated sine wave. Due to our modifications to the input signal, it is likely that this first sonification technique does not fit the traditional definitions of audification. Still, this strategy was simple and fairly direct, and certainly could be described as the least complex of the techniques that we developed.

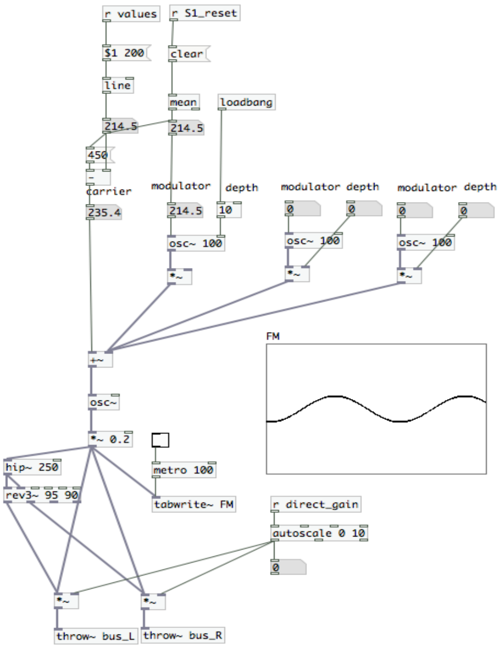


Figure 15: Direct sonification technique

2.4.2.2 Parameter Mapping Sonification

Surveying the literature, it seems that most of the techniques that are used in studies involving sonification could be described as parameter mapping sonification. Basically, this involves some feature or features of the input signal being mapped to or used to modulate some feature of the resultant output sound. The 2006 paper by Baier et al provided a good basis for sonifying a stream of data using this method [11].

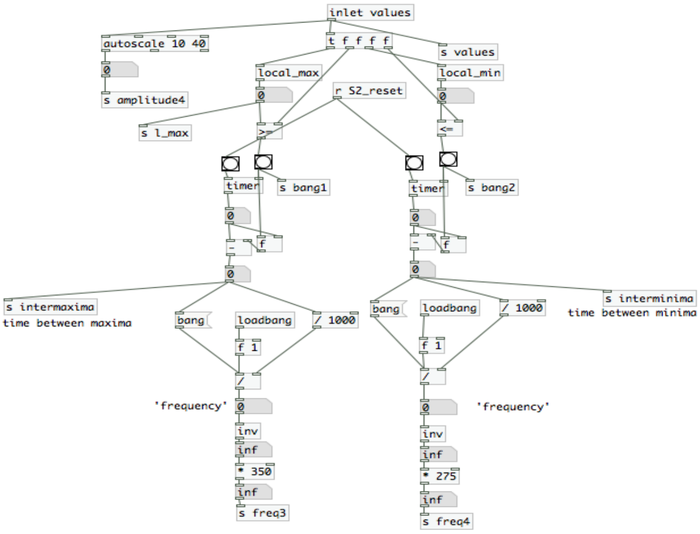


Figure 16: Feature extractor for detecting events for the parameter mapping technique.

In our parameter mapping sonification technique, the data was first sent to a feature extractor subpatch within Pd. The purpose of this subpatch is to detect and isolate the chosen events or features from the input signal and send them to the next part of the patch, which uses them to modulate various parameters of a sound. The sound in this case is an oscillator put through a voltage controlled filter. When data is streaming, the feature extractor detects each time a new local maximum or minimum occurs. This is accomplished with the "local_max" and "local_min" objects in Pd. The maxima and minima are actually affecting separate yet similar output sounds, which differ mainly in the way that the center frequency of the vcf is determined. The sounds, when triggered, take on the following parameters as determined by the data:

- The distance in time between each subsequent maximum or minimum is used to calculate the sustain of the resulting sounds' amplitude envelope. The patch is designed so that the output will have a generally fast envelope, but the length of the sustain is somewhat variable within a predetermined range.

- By keeping track of how many maxima or minima occurred each second, a crude estimation of the input signal's frequency could be calculated. This value was scaled, and the frequency of the maxima was used to modulate the center frequency of one sounds vcf, while the minima frequency modulated the center frequency of the second vcf.

- Lastly, the input values were directly scaled to affect the amplitude of both output sounds. In this way, higher relaxation values would yield louder sounds.

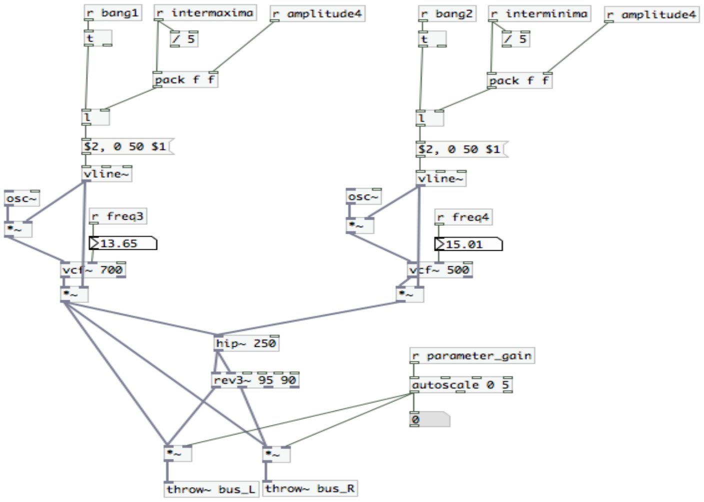


Figure 17: Parameter mapping sonification technique.

While this technique is surely more complex than the direct technique, it still follows certain predefined rules, and thus its output is somewhat predictable. Of the three techniques used in this research, parameter mapping sonification exists near the center of the simplicity-complexity spectrum.

2.4.2.3 Musical/Arbitrary Sonification

We have seen how EEG signals, BCIs and sonification techniques have been used in the past for the purposes of music composition and performance. In our research, we have used a technique that aims at a more inherently musical-sounding output for the third, and likely most complex technique.

Towards achieving the most simple musical output with this type of sonification, the strategy would likely involve mapping the incoming stream of data to frequency values and triggering bursts of sounds set to these notes. However, due to a number of reasons, both objective and subjective, a more thorough set of conditions was needed. After all, not all integer values in Hz correspond to a note in Western music, and playing a random sequence of such notes would certainly not correspond to any recognized scale. Thus the results would not be very musical, and would likely subjectively quite dissonant.

To create a more generally musical output, two important complexities were added to the scenario described above. First, although Pd is an excellent tool for audio and music synthesis in general, it was decided that MIDI would provide more flexibility with regards to the sounds triggered by the input data. By sending the data as MIDI messages, a number of different kinds of sounds could be auditioned quickly. Subsequent notes in Western music are assigned subsequent integer values, and so scaling the input data to integers would only trigger recognized notes if MIDI was used. The second important change was to restrict the MIDI output to values associated with certain notes. In this case, the 7 diatonic notes of a major scale (minus the octave) were used. A subpatch was written, based off of a patch concerned with using chaos theory in algorithmic composing. By using some relatively simple mathematical operations, the input stream can be scaled to select one of only seven preselected notes at a time. In a similar was, the input data were also streamed into a second subpatch designed to send groups of MIDI messages corresponding to the diatonic chords within the same major scale. By doing so, the data would be creating a melodic line in addition to the underlying chords. Since these all belonged to the same scale, a relatively consonant, if not melodically memorable, composition would be created in real time.

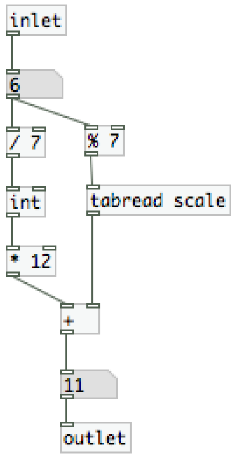


Figure 18: Subpatch for generating random diatonic pitches

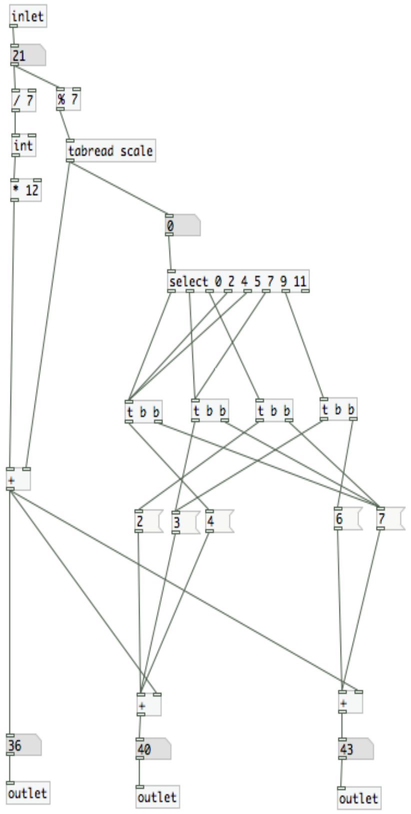


Figure 19: Quite similar to Figure 17, this subpatch is used for generating diatonic chords.

With melody and harmony taken care of, we could then move on to rhythm. Here, separate approaches were taken for the melodic line and the chords. The notes from the melody were played in a rhythm dictated by the “euclid” object in Pd. This object was specifically designed to output euclidian rhythms [90], which have onsets that are as evenly divided as possible given the input parameters. By adjusting these parameters, the tempo of the output can be adjusted, as can the number of beats per measure and how many notes can be in each measure as a maximum. While we chose to hold the number of beats per measure and the tempo constant, the maximum notes per measure parameter was constantly by sending it through the “drunk” object in Pd. This object outputs random numbers based around the input parameter. Meanwhile, the chords’ output was set to be triggered every 1000, 1500, 2500 or 3000 milliseconds, based on a random selection.

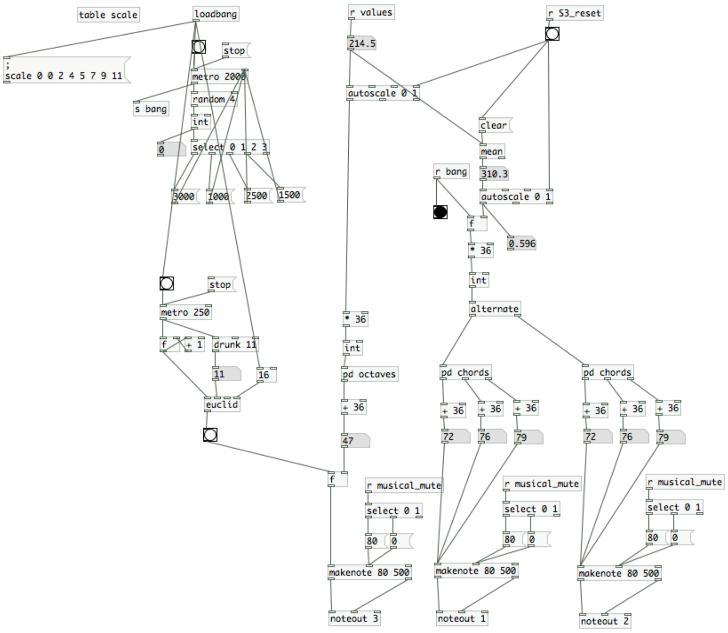


Figure 20: Musical/Arbitrary mapping technique.

For the MIDI output, the Ableton Live was used as a software platform. Separate patches were chosen for the melody and the chords, with the idea that they should be relatively pleasant and not distracting. Modifications were made from the stock patches to create longer reverb times and decay times. In fact, two identical sounds were used for the chords in Ableton, and their output was alternated from within Pd, so that each new triggered chord would not prematurely cut off the decay of the previous chord.

With these elements combined, a seemingly random, although actually rather complex, musical output was created. In general, since input data was scaled more or less directly, higher input values can be expected to produce higher notes within the scale.

3 Methods

3.1 Research Question

Our research is concerned with answering the following two-part question:

a) Can auditory display of brain activity be coherently perceived by a study subject as being representative of his/her internal brain and body states?

b) Once it has been clearly established that subjects are able to perceive auditory displays as being representative of their own brain activity - specifically, of relaxation states, which kind of sonification is best suited for the purpose?

   i. Direct Sonification/Audification

   ii. Parameter Mapping Sonification

   iii. Arbitrary/Musical Mapping

3.2 Experimental Design

3.2.1 Experimental Scope and Definitions

3.2.1.1 Sample

The sample size for our experiment consisted of 14 graduate and doctoral students, both male and female, from Universitat Pompeu Fabra. Their ages ranged from 23 to 36 years, with the mean being 28. These students had no prior specific knowledge of the experiment, although several were familiar with BCIs and the Emotiv EPOC in particular. None had participated in experiments involving sonification.

3.2.1.2 Measures

Over the course of the experiment, we kept track of the following subjective measures for each subject using a 5-point Likert scale:

i. Representation - How well did the sound reflect his/her state of relaxation?

ii. Sound description - How relaxing was the sound itself?

iii. Relaxation state - How relaxed do they feel now?

We also recorded objective data in the form of the alpha power values taken from the streaming EEG headset. Due to its association with relaxation states, we chose to concentrate on activity within the alpha band of the EEG. The physiological data and responses from the questionnaire were the dependent variables. Independent variables were the type of auditory feedback given to the subject (real-time sonification vs placebo) and the type of sonification:

- S1: Direct Sonification/Audification
- S2: Parameter Mapping Sonification

- S3: Arbitrary/Musical Mapping

3.2.1.3 Questionnaire

The questionnaire was designed to record subjective responses to each sonification separately based on the three measures described above (representation, sound description and relaxation state). Since each of the three sonifications, as well as the placebo recordings, were played twice per subject, that created a total of 36 responses per subject. These subjective results were used as the basis for part of the analysis. To avoid patterns and keep the subjects concentrated on the task of self-evaluation, the order of the three questions was randomized and the 5-point scale was sometimes reversed.

3.2.1.4 Recordings of Physiological Data

As described earlier, raw physiological data were recorded for all subjects using the GDF file writer module in OpenVibe. In addition, the calculated alpha band relative power that was used for input into the sonification engine was recorded in a separate .csv file. This allowed for the objective physiological analysis that will be discussed later.

3.2.2 Experimental Setting

In order to conduct the experiment, the following materials were gathered:

- A quiet room with adjustable lighting and sufficient soundproofing to avoid outside disturbances or distractions from outside.
- The Emotiv EPOC neuroheadset used for data acquisition.
- One laptop computer running the signal acquisition and processing modules as described in Section 2.1.
- One laptop computer running the sonification engine and playing the sonifications to the study subject in real time.
- A pair of loudspeakers to play the sonifications to the study subject.
- A checklist with the steps of the experiment clearly listed, with space to record deviations or observations.
- A second checklist with the specific order for the sonifications and placebos for each subject. Again, space for notes was included.
- A pair of loudspeakers, connected to the output of the sonification engine, that plays the selected sonification strategies back to the subject.

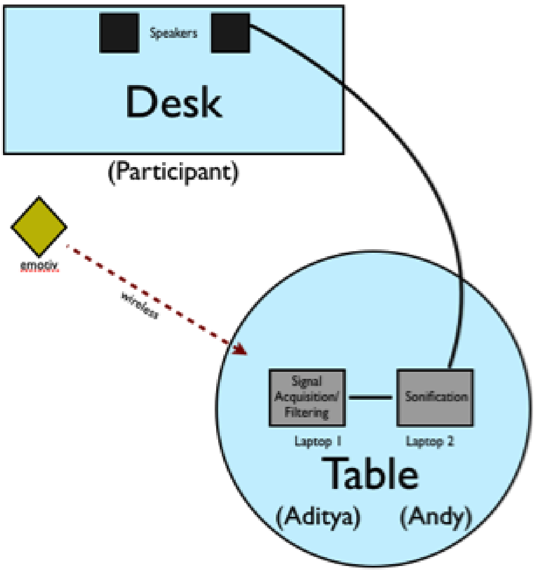


Figure 21: Diagram of experimental setup

3.2.3 Experimental Protocol

The protocol for our experiment consisted of the following steps:

- Introduction to the experiment – the subject is brought into the room, provided with a brief overview of the experiment and advised that he/she will be exposed to sonifications of his/her EEG signal.

- Demographics - The subject is assigned a unique ID to ensure anonymity. He/she provides his/her consent, demographic information as well as some information regarding musical ability and understanding of musical and electronic instruments.

- Fitting the device – the EPOC is fitted on to the subject's head. The Emotiv Test Bench software is used to verify that the electrodes are making a good connection to the scalp. The subject is asked to blink rapidly, clench their jaw, and look in various directions while the supervisor visually inspects the real-time EEG readout for responses to these actions.

- Normalization – Once the device has been fitted and signal acquisition has been insured, the subject is asked to relax while being exposed to four minutes of relaxing music. At the end of the four-minute listening session, the subjects are asked to record their current level of relaxation on a 5-point Likert scale.

- Experimental Set 1 – Once the subject is comfortable and ready to begin, the first set of sessions begins. The experiment is divided into two sets of sessions which are separated by a two-minute break. Each set contains six sessions of sonifications of two minutes length each. The order of the sonifications is randomized for every subject. The six sessions consist of three real-time sonifications and three placebo sonifications of the same types, such that each type is represented twice per set - once as an actual sonification and once as a placebo. Between each sonification, there is a break for approximately one minute. During this time, the subject will be asked to fill in a questionnaire (5-point Likert grading) to self-evaluate the following:

i. Representation - How well did the sound reflect his/her state of relaxation?

ii. Sound description - How relaxing was the sound itself?

iii. Relaxation state - How relaxed does the subject feel now?

- Break - After the first set of six sonifications is complete, the subject is allowed a slightly extended break of two minutes. During this break, the supervisors do not converse with the subject in order to maintain the state of the subject as far as possible. The objective is to avoid listening fatigue.

- Self-evaluation-Prior to starting the second set of sessions, the subject will be asked to enter his/her self-evaluated state of relaxation once again, just as he/she had before beginning the experiment.

- Experimental Set 2 - The second set of sessions begins, following the process described in step 5.

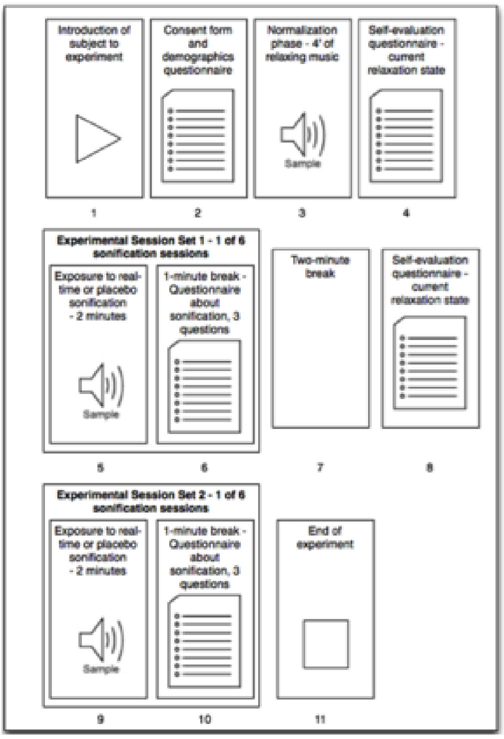


Figure 22: Step-by-step explanation of experiment.

After both sets of sessions are over, the experiment is complete and the subject free to leave. A graphical overview of the experimental procedure is provided in Figure 22.

3.4 Hypotheses

We hypothesize that concerning the **type of feedback** exposed to the subject:

i. Real-time sonifications will be viewed as more representative of relaxation states than the placebos.

ii. Real-time sonifications will be viewed as more relaxing than the placebos.

iii. Subjects will feel more relaxed after listening to real-time sonifications than placebos.

We further hypothesize that concerning the **type of sonification** exposed to the subject:

i. Direct sonification will be viewed as more representative of relaxation states than the more musical techniques.

ii. Direct sonification will be viewed as less relaxing than the more musical techniques.

iii. Subjects will feel less relaxed after listening to direct sonifications than the more musical techniques

4. Results and Analysis

In this section, strategies and methods for analyzing our experimental data are outlined.

4.1 Analysis Strategy

The strategy for evaluating our rather large dataset consists of utilizing the data collected via the questionnaire, which is more subjective in nature, and the physiological data, which is objective. Due to a considerable difference in the range of physiological data collected for each subject, we have evaluated both absolute and relative values for this data.

Our dataset consists of five variables:

- Representation (subjective)
- Sound Description (subjective)
- Relaxation State (subjective)
- Alpha Power-Absolute (objective)
- Alpha Power-Relative (objective)

For each of these, the following analyses were done:

1. Primary Analyses:
    a) Real-time Sonification vs. Placebo recordings per sonification strategy.
    b) Comparison among the three sonification strategies (real-time only).
2. Secondary Analyses:
    a) Correlation analyses between Representation, Sound Description and Relaxation State
    b) Correlation analyses between physiological data and Sound Description.
    c) Correlation analyses between physiological data and Relaxation State.

4.2 Evaluation Methods

4.2.1 Questionnaire Data

Responses from the questionnaires were compiled and separate datasets for each of the three subjective variables were created. For each dataset, means were calculated over the complete set of sonifications, using both real-time sonifications and placebo recordings. Statistical analysis software SPSS was used to perform t-tests between these mean values as well as among individual real-time and placebo sessions for each type of sonification.

- Total real-time sonification data vs Total placebo sonification data.
- Direct mapping (S1) vs. its corresponding placebo (P1)
- Parameter mapping (S2) vs. its corresponding placebo (P2)
- Musical mapping (S3) vs. its corresponding placebo (P3)

The sonification strategies were then compared with each other with t-tests:

- S1 vs. S2
- S1 vs. S3
- S2 vs S3

4.2.2 Physiological Evaluation

The physiological data recorded during each session was processed using the EEGLAB toolbox within MATLAB, using an automated script. The script outputs the average power of the alpha band for each sonification session. This script can be found in Appendix C.

By using this method, complete tables of physiological means could be compiled, similar to those complies from the questionnaire data. These tables were thus properly formatted to be analyzed within SPSS.

Because of deviations in the range of physiological data, as mentioned above, we added an additional variable of the normalized alpha band power vales. The relative alpha band power was calculated in this way:

Relative Alpha Band Power = Session Average / Maximum Alpha Band Power from all sessions

The result from this calculation was a new value for the alpha power, with a range of 0 to 1.

4.3 Results

4.3.1 Investigation of Means

As a first step, we have examined the means of subjective and objective data, looking for general trends that may or may not be consistent with our primary hypothesis.

4.3.1.1 Real-time Sonification vs. Placebos

The mean values were derived from the tables in Appendix A over the values for each sonification strategy from each of the two cycles, e.g.:

Mean S1 = (C1S1 + C2S1)/2

Where:

C1S1 = Cycle 1 Direct Mapping Session

C2S1 = Cycle 2 Direct Mapping Session

This method was used for all strategies and their respective placebo sessions.

Finally, the aggregate means were derived as follows:

Aggregate Real-Time Mean = (S1+S2+S3)/2

Aggregate Placebo Mean = (P1+P2+P3)/2

Where:

S1, S2, S3 = Means of direct, parametric and musical mapping real-time sonification sessions respectively

P1, P2, P3 = Means of direct, parametric and musical mapping real-time placebo sessions respectively

The following table shows the results:

	REAL-TIME			PLACEBO			Aggregate Mean Real-Time	Aggregate Mean Placebo
Variable	**Mean S1**	**Mean S2**	**Mean S3**	**Mean P1**	**Mean P2**	**Mean P3**		
Representation	2.75	3.38	3.21	2.92	3.75	2.88	3.11	3.18
Sound Description	2.00	3.83	3.21	2.29	3.46	3.04	3.01	2.93
Relaxation State	3.38	3.17	3.63	4.04	3.96	3.88	3.68	3.67
Physiology (Absolute)	4.12	4.47	4.37	4.11	4.25	4.33	4.32	4.23
Physiology (Relative)	0.70	0.75	0.74	0.66	0.71	0.70	0.73	0.69

Table 1. Average results of Real-Time and Placebo sonification sessions

The units for these variables are:

- Representation, Sound Description, Relaxation State–5-point Likert scale corresponding to the questionnaire.
- Physiology (Absolute) - Alpha Band Power, μV^2
- Physiology (Relative) – normalized values ranging from 0 to 1

From this table we can see that there is no strong trend in favor of real-time or placebo sonifications can be identified.

4.3.2 Parametric Analyses

In this section, independent sample t-tests are performed to look for potentially deeper significance within the calculated mean values. Since different conditions are independent of each other, and this is reinforced by randomization of sounds to avoid bias and patterns, the design can be considered an unrelated design, thus independent t-tests are used.

This analysis is done in two parts. Firstly, real-time sonifications are compared to placebos to test for significant differences in subjects' responses. Secondly, the real-time sonification techniques are tested against one another.

4.3.2.1 Real-Time vs Placebo Sonifications

The results from the independent t-tests are shown in the following table.

	Representation	Sound Description	Relaxation Effect	Alpha Band Power (Absolute)	Alpha Band Power (Relative)
AGGREGATE: Mean (All RT) vs Mean (All PL)	0.703	0.740	0.963	0.932	0.847
DIRECT MAPPING					
Comparison of means	0.622	0.503	0.621	0.995	0.877
C1S1 vs. C1PL1	0.866	0.274	0.470	0.965	0.836
C2S1 vs. C2PL1	0.609	0.842	0.858	0.961	0.500
PARAMETER MAPPING					
Comparison of means	0.355	0.388	0.834	0.831	0.832
C1S2 vs. C1PL2	0.870	0.792	0.729	0.848	0.547
C2S2 vs. C2PL2	0.198	0.280	0.455	0.821	0.717
ARBITRARY/MUSICAL MAPPING					
Comparison of means	0.234	0.672	0.418	0.971	0.867
C1S3 vs. C1PL3	0.112	0.603	0.618	0.826	0.790
C2S3 vs. C2PL3	0.636	0.869	0.441	0.775	0.341

Table 2. Results of t-tests between real-time and placebo sonifications

Using a confidence interval of $p < 0.05$, none of these results support a significant difference in the subjects' response to placebo vs real-time sonifications.

4.3.2.2 Comparison of Sonification Strategies

Questionnaire responses for real-time sessions of all sonification strategies were compared with each other, using both the mean values and the values for each six-session cycle. In the following tables, significant results are highlighted with an asterisk. To further illustrate the differences in means, a graph showing the sonifications with significant differences means is included here.

Data source	Representation	Sound Description	Relaxation Effect	Alpha Band Power (Absolute)	Alpha Band Power (Relative)
Comparison of means	0.116	0.000*	0.079	0.728	0.278
Cycle 1	0.061	0.012*	0.156	0.736	0.632
Cycle 2	0.640	0.000*	0.122	0.734	0.435

Table 3. Parametric analysis between direct (S1) and parameter mapping (S2); p<0.05

In terms of sound description, we see a clear significance when comparing direct mapping and parameter mapping. This means that subjects found parameter mapping (S2) to be more relaxing.

Data source	Representation	Sound Description	Relaxation Effect	Alpha Band Power (Absolute)	Alpha Band Power (Relative)
Comparison of means	0.142	0.012*	0.523	0.802	0.300
Cycle 1	0.110	0.005*	0.307	0.858	0.875
Cycle 2	0.583	0.079	0.858	0.761	0.429

Table 4. Parametric analysis between direct (S1) and musical mapping (S3); p<0.05

Data source	Representation	Sound Description	Relaxation Effect	Alpha Band Power (Absolute)	Alpha Band Power (Relative)
Comparison of means	0.625	0.095	0.241	0.919	0.974
Cycle 1	0.453	0.752	0.560	0.871	0.721
Cycle 2	1.000	0.040*	0.190	0.969	0.916

Table 5. Parametric analysis between parameter (S2) and musical mapping (S3); p<0.05

The following graphs plot the means of S1 vs S2 and S1 vs S3 for all subjects:

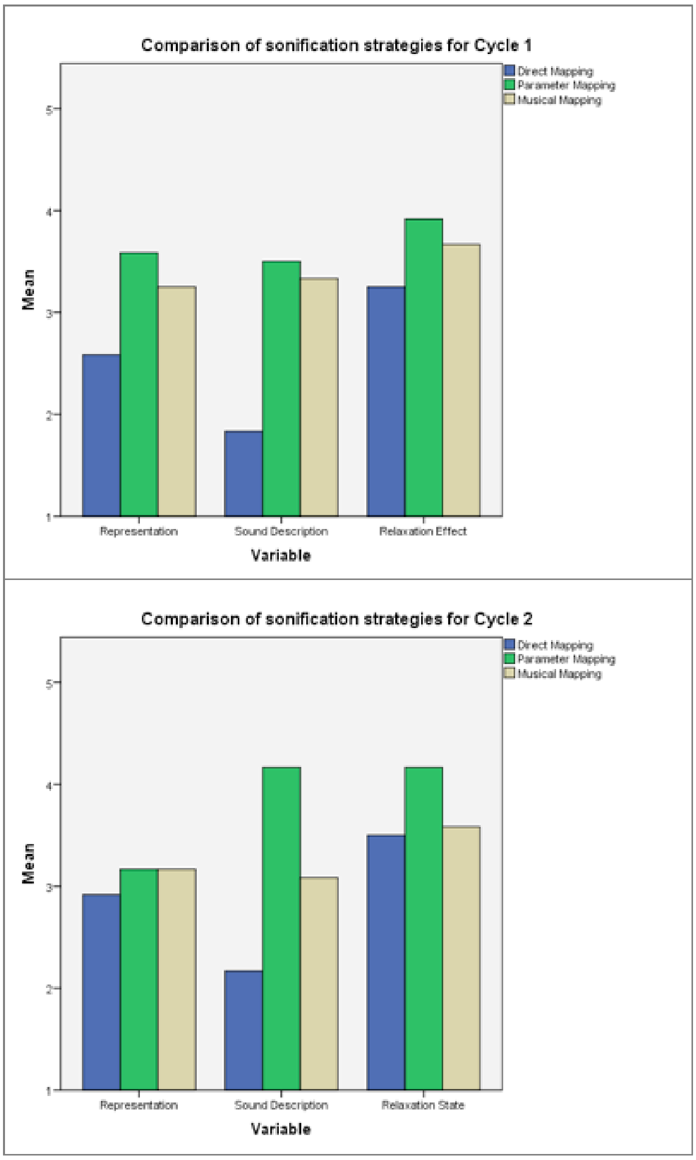


Table 6. Differences between reponses to sonification strategies

4.3.3 Correlation Analysis

As a next step, correlation analysis was done over the entire dataset to examine if and how the variables affect each other. A summary table for the correlation analysis can be found below:

Correlations						
		Represenuation	Sound Description	Relaxation State	Physiology (Absolute)	Physiology (Relative)
Represent-ation	Pearson Correlation	1	.243*	.179	-.134	-.094
	Sig. (2-tailed)		.040	.133	.263	.434
	N	72	72	72	72	72
Sound Description	Pearson Correlation	.243*	1	.306**	-.101	-.038
	Sig. (2-tailed)	.040		.009	.397	.751
	N	72	72	72	72	72
Relaxation State	Pearson Correlation	.179	.306**	1	-.038	.005
	Sig. (2-tailed)	.133	.009		.749	.967
	N	72	72	72	72	72
Physiology (Absolute)	Pearson Correlation	-.134	-.101	-.038	1	.643**
	Sig. (2-tailed)	.263	.397	.749		.000
	N	72	72	72	72	72
Physiology (Relative)	Pearson Correlation	-.094	-.038	.005	.643**	1
	Sig. (2-tailed)	.434	.751	.967	.000	
	N	72	72	72	72	72
*. Correlation is significant at the 0.05 level (2-tailed).						
**. Correlation is significant at the 0.01 level (2-tailed).						

Table 7. Correlation data for the complete data set.

The next table summarizes the areas in which significance was found:

	Representation	**Sound Description**	**Relaxation State**	**Physiology (Abs)**	**Physiology (Rel)**
Representation	■	*			
Sound Description	*	■	**		
Relaxation State		**	■		
Physiology (Abs)				■	■
Physiology (Rel)				■	■
**. Correlation is significant at the 0.01 level (2-tailed).					
*. Correlation is significant at the 0.05 level (2-tailed).					

Table 8. Correlation between variables

From this table, we can make some interesting observations about the results from our experiment. The significant positive correlation between Sound Description and Relaxation can likely be expected, because the questions share some similarity. After all, if a subject finds a sound to be relaxing, it's logical that the subject would exhibit signs of relaxation following that sound. However, no significance was found between the subjective inputs and the physiological data.

We can therefore infer that the perceived level of relaxation of a given strategy also effects whether that same strategy is considered to be representative or not. In other words, subjects are more likely to describe a strategy as representative if it is also relaxing.

5. Discussion and Conclusions

5.1 Discussion

5.1.1 Summary of Results

From the above analyses, we can summarize the findings from our experiment:

1. No trends in favor of real-time sonifications or placebos are present.
2. No significance is observed in parametric analyses between real-time and placebo sonifications. The primary hypothesis based on this can thus be rejected for sound description.
3. In terms of sound descriptions, clear trends in favor of parameter mapping and musical mapping as opposed to direct sonification are noted. Our hypothesis stating that the more musical mappings (S2 and S3) will be found to be more relaxing than the direct sonification technique is supported by the data.
4. Sound description shows very strong correlation at the $p < 0.05$ level with Representation.

5.1.2 Real-time vs. Placebo Sonifications

Our original hypothesis, in which we believed that real-time sonifications would be seen as more representative and relaxing than placebo sonifications, had to be rejected because of a lack of significance.

One possible reason for this outcome is the specific design of the placebos for our experiment. For example, we created 12 placebo recordings, two for each of the three sonification strategies. During the experiment, each subject heard 12 different placebos. As we saw from the data, the placebo recordings were found to be almost equally relaxing, and sometimes more relaxing, than the real-time sonifications themselves. Also, the placebo recordings were made in an identical setting to the experiment, in a quiet room with the subject's eyes closed throughout. Perhaps further investigation into this matter is warranted. A follow-up experiment could be designed using a larger, more varied set of placebo recordings, since our experimental data involved quite a range of alpha power values. It would make sense to create placebo recordings that represent this variety. These recordings could be made from subject in a similar setting to our experiment, from a subject in conditions different from our experiment (noisy room, eyes open, with different stimuli), or from some type of random number generator.

5.1.3 Comparison of Sonification Strategies

After comparing the three sonification strategies used in this research, our hypothesis proposing that more musical sonifications would be perceived as being more relaxing than a more direct mapping was confirmed. However, no correlation was found between the sonifications strategies and the physiological data to confirm that any relaxing effect was induced by the stategies.

Despite this, we feel there is good evidence to support continued exploration of the parameter mapping technique within a biofeedback paradigm. Perhaps an experiment using this strategy by itself for some sort of relaxation task would be feasible.

5.1.4 Experimental Design Factors

We acknowledge the possibility that the design and execution of our experiment may have had an unwanted effect on our findings. Our experiment, even when it was efficiently-run and there were no technological issues, took at least 45 minutes. Occasional issues such as difficulty in acquiring signal from some subjects due to excess hair, or minor faults within our rather complex system caused delays that sometimes significantly lengthened the experiment and perhaps affected subjects' level or relaxation. The possibility of listening fatigue, based on the experiment being too long or any other reason, could be seen as a source of bias.

Furthermore, we acknowledge that the lack of a training period in our experiment may have contributed to our lack of significant results. Subjects in our experiment were informed that they would be listening to their own body signals, but no training or guidance was introduced in order for subjects to knowingly control the sonifications. In biofeedback experiments that require control of a system, training periods are essential. We would be interested to see the results of a similar experiment with the addition of a training portion.

5.2 Future Work

Based on the literature review and our experiments, it seems that future experiments could certainly done along these same lines. Surely, the strategy that was found to be most relaxing, parameter-mapping sonification, could be investigated and modified further. Also, additional sonification strategies, techniques and mappings could be tried. Early in our research, granular synthesis seemed to exhibit potential based on its flexibility. Further experiments could use this type of synthesis as a basis for sonification. There are other possibilities as well for creating a simple, more direct technique. Additive, subtractive and wavetable synthesis might also offer simple yet flexible options for sonification techniques.

5.3 Conclusion

Sonification within a biofeedback paradigm has not been widely explored as a research topic. We consider our work, in which a system capable of providing a number of different types of sonification for testing within just such a system, to be a partial success since one of our hypotheses was confirmed by the data. This research provides some valuable insight into sound perception as it relates to biofeedback and sonification, and we believe that our work could be used in support of future exploration into this type of auditory display.

References

(1) SuperCollider. Available at: www.audiosynth.com. Accessed March 28, 2012.
(2) Max/MSP. Available at: http://cycling74.com/. Accessed March 28, 2012.

(3) Emotiv EPOC neuroheadset. Available at: http://www.emotiv.com/apps/epoc/299/, 2012.

(4) Available at: http://www.neurodevelopmentcenter.com/uploads/pics/eeg_traces_01.gif. Accessed August 26, 2012.

(5) EEGLAB - Open Source Matlab Toolbox for Electrophysiological Research. Available at: http://sccn.ucsd.edu/eeglab/. Accessed August 27, 2012.

(6) OpenViBE | Software for Brain Computer Interfaces and Real Time Neurosciences. Available at: http://openvibe.inria.fr/. Accessed August 27, 2012.

(7) Adrian ED, Matthews BHC. The Berger rhythm: potential changes from the occipital lobes in man. Brain 1934;57(4):355-385.

(8) Arslan B, Brouse A, Castet J, Filatriau JJ, Léhembre R, Noirhomme Q, et al. From biological signals to music. 2005.

(9) Auenbrugger L, Forbes J, Sigerist H. On Percussion of the Chest. ; 1936.

(10) The sonification of rhythms in human electroencephalogram. Proceedings of ICAD: Citeseer; 2004.

(11) Sonified epileptic rhythms. Proceedings of the International Conference on Auditory Display, London, UK; 2006.

(12) Baier G, Hermann T, Stephani U. Event-based sonification of EEG rhythms in real time. Clinical Neurophysiology 2007;118(6):1377-1386.

(13) Multi-channel sonification of human EEG. Proc. Intl. Conf. Auditory Display (ICAD),(Montreal, Canada); 2007.

(14) Baier G, Sahle S. Listening to Chaos: the Aural Representation of Irregular Rhythms. Sciences of the Interface, Genista Verlag, Tübingen 2001:255.

(15) Baier[1] G, Hermann T, Lara[1] OM, Müller[1] M. Using sonification to detect weak cross-correlations in coupled excitable systems. 2005.

(16) Improved topological fiducial tracking in the reactivision system. Computer Vision and Pattern Recognition-Workshops, 2005. CVPR Workshops. IEEE Computer Society Conference on: Ieee; 2005.

(17) Bernstein J, & C.Schönlein. Telephonische Wahrnehmungder Schwankungendes Muskelstromes bei der Contraction. Sitzungsberichte der Naturforschenden Gesellschaft zu Halle:18–27. (1881).

(18) Bierbaumer N, Ghanayim N, Hinterberger T, Iversen I, Kotchoubey B, Kubler A, et al. A Spelling Device for the Paralyzed. Nature 1999;398:297-298.

(19) Birbaumer N. Breaking the silence: brain–computer interfaces (BCI) for communication and motor control. Psychophysiology 2006;43(6):517-532.

(20) Birbaumer N, Elbert T, Rockstroh B, Lutzenberger W. Biofeedback of event-related slow potentials of the brain. International Journal of Psychology 1981;16(1-4):389-415.

(21) Bly S. Sound and computer information presentation 1982.

(22) Chambers J, Mathews M, Moore F. Auditory data inspection. Report TM 1974:74-122.

(23) Chowning J. The synthesis of complex audio spectra by means of frequency modulation. Journal of the Audio Engineering Society 1973;21(7):526-534.

(24) Auditory seismology: on free oscillations, focal mechanisms, explosions and synthetic seismograms. Proceedings of the 8th International Conference on Auditory Display; 2002.

(25) Dombois F, Eckel G. Audification. The Sonification Handbook 2011:301-324.

(26) Frantti G, Levereault L. Auditory discrimination of seismic signals from earthquakes and explosions. Bulletin of the Seismological Society of America 1965;55(1):1-25.

(27) Applied research in auditory data representation. Proceedings of SPIE; 1990.

(28) Gaver WW. The SonicFinder: An interface that uses auditory icons. Hum -Comput Interact 1989;4(1):67-94.

(29) Gelatt R. The fabulous phonograph, 1877-1977. : Macmillan New York; 1977.

(30) Giardino ND, Chan L, Borson S. Combined heart rate variability and pulse oximetry biofeedback for chronic obstructive pulmonary disease: preliminary findings. Appl Psychophysiol Biofeedback 2004;29(2):121-133.

(31) Composing with brainwaves: minimal trial P300b recognition as an indication of subjective preference for the control of a musical instrument. Proceedings of International Cryogenic Materials Conference (ICMC'08); 2008.

(32) Grond F, Berger J. Parameter Mapping Sonification. In: Hermann T, Hunt A, Neuhoff JG, editors. The Sonification Handbook Berlin: Logos Verg; 2011. p. 363-397.

(33) Brain-Computer Interface (BCI) Based Musical Composition. Cyberworlds (CW), 2010 International Conference on: IEEE; 2010.

(34) Listening to the earth sing. SANTA FE INSTITUTE STUDIES IN THE SCIENCES OF COMPLEXITY-PROCEEDINGS VOLUME-: ADDISON-WESLEY PUBLISHING CO; 1994.

(35) Hermann T. Model-based Sonification. In: Hermann T, Hunt A, Neuhoff JG, editors. The Sonification Handbook Berlin: Logos Verlag; 2011. p. 399-419.

(36) Hermann T. Sonification - A Definition. 2010; Available at: http://sonification.de/son/definition. Accessed March 29, 2012.

(37) Taxonomy and definitions for sonification and auditory display. Proceedings of the 14th international conference on auditory display; 2008.

(38) Tangible computing for interactive sonification of multivariate data. Proceedings of the 2nd Interactive Sonification Workshop; 2007.

(39) The discipline of interactive sonification. Proceedings of the Int. Workshop on Interactive Sonification; 2004.

(40) Hermann T, Meinicke P, Bekel H, Ritter H, Müller HM, Weiss S. Sonification for eeg data analysis. 2002.

(41) Hermann T, Ritter H. Sound and meaning in auditory data display. Proc IEEE 2004;92(4):730-741.

(42) Hill NJ, Lal TN, Bierig K, Birbaumer N, Schölkopf B. An Auditory Paradigm for Brain--Computer Interfaces. 2004.

(43) Hinterberger T. The Sensorium: A Multimodal Neurofeedback Environment. Advances in Human-Computer Interaction 2010;2011.

(44) Hinterberger T, Baier G. Parametric orchestral sonification of EEG in real time. Multimedia, IEEE 2005;12(2):70-79.

(45) Hinterberger T, Kübler A, Kaiser J, Neumann N, Birbaumer N. A brain-computer interface (BCI) for the locked-in: comparison of different EEG classifications for the thought translation device. Clinical Neurophysiology 2003;114(3):416-425.

(46) Hinterberger T, Neumann N, Pham M, Kübler A, Grether A, Hofmayer N, et al. A multimodal brain-based feedback and communication system. Experimental Brain Research 2004;154(4):521-526.

(47) Hinterberger T, Schmidt S, Neumann N, Mellinger J, Blankertz B, Curio G, et al. Brain-computer communication and slow cortical potentials. Biomedical Engineering, IEEE Transactions on 2004;51(6):1011-1018.

(48) The reacTable: exploring the synergy between live music performance and tabletop tangible interfaces. Proceedings of the 1st international conference on Tangible and embedded interaction: ACM; 2007.

(49) Jovanov E, Marsh A, Obrenovic Z. EEG analysis in a telemedical virtual world. Future Generation Comput Syst 1999;15(2):255-263.

(50) Kaiser W, Greiner H. Warning system for printing presses 1980.

(51) TUIO: A protocol for table-top tangible user interfaces. Proc. of the The 6th Int’l Workshop on Gesture in Human-Computer Interaction and Simulation; 2005.

(52) Kamiya J. Operant control of the EEG alpha rhythm and some of its reported effects on consciousness. Altered states of consciousness.New York: Wiley 1969:507-517.

(53) Kiefer P editor. Klangräume der Kunst. Heidelberg: Kehrer; 2012.

(54) Kittler F, von Mücke D, Similon PL. Gramophone, film, typewriter. October 1987;41:101-118.

(55) Klonowski W, Perovic A, Jovanovic A. Some computational aspects of the brain computer interfaces based on inner music. Computational intelligence and neuroscience 2009;2009.

(56) Kogure M, Matsuzaki S, Wada Y. Investigation of brain-computer interfaces that apply sound-evoked event-related potentials. Artificial Neural Networks–ICANN 2010 2010:127-134.

(57) Kramer G, Santa Fe Institute (Santa Fe, NM). Auditory display: Sonification, audification, and auditory interfaces. : Addison-Wesley; 1994.

(58) Kramer G, Santa Fe Institute (Santa Fe, NM). Introduction. Auditory display: Sonification, audification, and auditory interfaces: Addison-Wesley; 1994.

(59) Kramer G, Walker B, Bonebright T, Cook P, Flowers JH, Miner N, et al. Sonification report: Status of the field and research agenda. 2010.

(60) Kunsthalle Bern editor.
Florian Dombois:What Are the Places of Danger. Works 1999-2009. Berlin: argobooks; 2010.

(61) Laennec RTH, Forbes SJ. A treatise on the diseases of the chest and on the mediate auscultation. : S. Wood & Sons; 1830.

(62) Lubar JO, Lubar JF. Electroencephalographic biofeedback of SMR and beta for treatment of attention deficit disorders in a clinical setting. Appl Psychophysiol Biofeedback 1984;9(1):1-23.

(63) Lutzenberger W, Elbert T, Rockstroh B, Birbaumer N. Biofeedback of slow cortical potentials. II. Analysis of single event-related slow potentials by time-series analysis. Electroencephalogr Clin Neurophysiol 1980;48(3):302-311.

(64) Malmivuo J, Plonsey R. Bioelectromagnetism: principles and applications of bioelectric and biomagnetic fields. : Oxford University Press, USA; 1995.

(65) Interactive Sonification for exploring Single Molecule Properties with AFM based Force Spectroscopy. Proceedings of the International Workshop on Interactive Sonification (ISon 2004), Bielefeld, Germany, Bielefeld University, Interactive Sonification Community peer-reviewed article; 2004.

(66) Mealla S, Väljamäe A, Bosi M, Jordà S. Listening to Your Brain: Implicit Interaction in Collaborative Music Performances.

(67) Meier M, Saranti A. SONIC EXPLORATIONS WITH EARTHQUAKE DATA.

(68) Meinicke P, Hermann T, Bekel H, Müller HM, Weiss S, Ritter H. Identification of discriminative features in the EEG. Intelligent Data Analysis 2004;8(1):97-107.

(69) Mezrich J, Frysinger S, Slivjanovski R. Dynamic representation of multivariate time series data. Journal of the American Statistical Association 1984:34-40.

(70) Miranda E, Brouse A, Boskamp B, Mullaney H. Plymouth brain-computer music interface project: Intelligent assistive technology for music-making. URL http://cmr.soc.plymouth.ac.uk 2005.

(71) Miranda ER, Matthias J. Music Neurotechnology for Sound Synthesis: Sound Synthesis with Spiking Neuronal Networks. Leonardo 2009;42(5):439-442.

(72) Miranda ER, Sharman K, Kilborn K, Duncan A. On harnessing the electroencephalogram for the musical braincap. Computer Music Journal 2003;27(2):80-102.

(73) Niedermeyer E, da Silva F. **Electroencephalography:** Basic Principles, Clinical Applications, and Related Fields. 5th ed.: Lippincott Williams & Wilkins; 2005.

(74) Nijboer F, Furdea A, Gunst I, Mellinger J, McFarland DJ, Birbaumer N, et al. An auditory brain-computer interface (BCI). J Neurosci Methods 2008;167(1):43-50.

(75) Nolte J. The human brain: An introduction to its functional anatomy. 2002.

(76) NÚÑEZ B, MANUEL I. EEG artifact detection. 2011.

(77) A comparison of audio and visual analysis of complex time-series data sets. Proceedings of ICAD 05-Eleventh Meeting of the International Conference on Auditory Display; 2005.

(78) Peretz I. The nature of music from a biological perspective. Cognition 2006;100(1):1-32.

(79) Pereverzev S, Loshak A, Backhaus S, Davis J, Packard R. Quantum oscillations between two weakly coupled reservoirs of superfluid 3He. Nature 1997;388(6641):449-450.

(80) Pollack I, Ficks L. Information of elementary multidimensional auditory displays. J Acoust Soc Am 1954;26:155.

(81) Riehle A, Vaadia E. Motor cortex in voluntary movements: a distributed system for distributed functions. : CRC; 2005.

(82) Rosenboom D. Extended musical interface with the human nervous system. Leonardo Monograph Series 1990(1).

(83) Rosenboom D. Biofeedback and the arts, results of early experiments. : Not Avail; 1976.

(84) Scaletti C, Craig AB. Using sound to extract meaning from complex data. World 1991;2:3.

(85) An auditory display for exploratory visualization of multidimensional data. Proceedings of the IFIP WG 5.10 International Working Conference on Workstations for Experiments: Springer-Verlag; 1989.

(86) Sörnmo L, Laguna P.

The electroencephalogram - A brief background. : Academic Press; 2005.

(87) Speeth SD. Seismometer sounds. J Acoust Soc Am 1961;33:909.

(88) Sterman M, Macdonald L, Stone RK. Biofeedback training of the sensorimotor electroencephalogram rhythm in man: effects on epilepsy. Epilepsia 1974;15(3):395-416.

(89) Mind-modulated music in the mind attention interface. Proceedings of the 19th Australasian conference on Computer-Human Interaction: Entertaining User Interfaces: ACM; 2007.

(90) The Euclidean algorithm generates traditional musical rhythms. Proceedings of BRIDGES: Mathematical Connections in Art, Music and Science; 2005.

(91) Vamvakousis Z.

vrpn2osc.exe. 2012.

(92) Vidal JJ. Toward direct brain-computer communication. Annu Rev Biophys Bioeng 1973;2(1):157-180.

(93) Walker BN, Kramer G. Ecological psychoacoustics and auditory displays: Hearing, grouping, and meaning making. Ecological psychoacoustics 2004:150-175.

(94) Wedenskii N(. Die telephonischen Wirkungendeserregten Nerven. Centralblattfürdiemedicinischen Wissenschaften 1883;31(26):465-468.

(95) Williams PL. Gray's anatomy. : Churchill livingstone London; 1989.

(96) Wolff R. Sounding out images. Anthology Computers in Physics Year 1992;6(3):287-289.

(97) Wolpaw JR, McFarland DJ, Neat GW, Forneris CA. An EEG-based brain-computer interface for cursor control. Electroencephalogr Clin Neurophysiol 1991;78(3):252-259.

(98) Wu D, Li C, Yin Y, Zhou C, Yao D. Music composition from the brain signal: representing the mental state by music. Computational intelligence and neuroscience 2010;2010:14.

(99) Wu D, Li CY, Yao DZ. Scale-free music of the brain. PloS one 2009;4(6):e5915.

(100) Pure Data. Available at:www.puredata.info. Accessed March 28, 2012.

(101) Zaccaria, G. M. (2011). Sonification of EEG signals A study on alpha band instantaneous coherence.

[102] Jasper HH. The ten-twenty electrode system of the International Federation. Electroencephalogr Clin Neurophysiol 1958;10(2):371-375.

Appendix A

Questionnaire Responses

Representation:

								Cycle 1							Cycle 2													
ID	Age	Nationality	Ability_Gen	Composition	Ability_Elec	Understanding	Relaxation_Init	S1	S2	S3	PL1	PL2	PL3	Relaxation_Interval	S1	S2	S3	PL1	PL2	PL3	Mean S1	Mean PL1	Mean S2	Mean PL2	Mean S3	Mean PL3	Agg. RT	Agg. PL
EXP001	26	Thai	1	1	1	1	4	1	5	3	1	4	4	4	3	3	4	5	3	1	2	3	4	3.5	3.5	2.5	3.167	3.000
EXP003	25	Spanish	3	5	4	5	4	3	4	4	3	4	4	4	5	3	3	4	2	4	4	3.5	3.5	3	3.5	4	3.667	3.500
EXP004	26	Indian	4	3	4	5	5	3	2	3	4	5	1	5	3	5	3	3	5	2	3	3.5	3.5	5	3	1.5	3.167	3.333
EXP005	28	Brazilian	5	5	5	4	4	4	4	3	4	4	2	4	4	2	1	3	5	4	4	3.5	3	4.5	2	3	3.000	3.667
EXP006	36	Colombian	5	5	5	5	5	2	2	2	4	5	2	5	2	1	4	2	5	2	2	3	1.5	5	3	2	2.167	3.333
EXP007	36	American	5	5	5	5	3	1	1	4	1	2	4	3	2	4	2	4	4	4	1.5	2.5	2.5	3	3	4	2.333	3.167
EXP009	25	Colombian	4	3	3	3	4	4	4	4	2	4	2	4	1	4	3	4	3	4	2.5	3	4	3.5	3.5	3	3.333	3.167
EXP010	34	Greek	1	1	1	2	5	3	5	4	2	5	4	5	2	5	5	2	5	3	2.5	2	5	5	4.5	3.5	4.000	3.500
EXP011	24	Colombian	4	2	3	4	2	4	3	2	3	2	2	2	4	2	4	4	3	4	4	3.5	2.5	2.5	3	3	3.167	3.000
EXP012	23	Turkey	5	2	3	3	4	1	5	4	1	4	3	4	3	4	3	1	4	2	2	1	4.5	4	3.5	2.5	3.333	2.500
EXP013	30	Ecuador	2	3	4	4	4	3	4	3	4	2	1	4	2	1	3	2	3	4	2.5	3	2.5	2.5	3	2.5	2.667	2.667
EXP014	24	Turkish	2	1	2	3	4	2	4	3	3	3	2	4	4	4	3	4	4	4	3	3.5	4	3.5	3	3	3.333	3.333

Sound Description:

								Cycle 1							Cycle 2													
ID	Age	Nationality	Ability_Gen	Composition	Ability_Elec	Understanding	Relaxation_Init	S1	S2	S3	PL1	PL2	PL3	Relaxation_Interval	S1	S2	S3	PL1	PL2	PL3	Mean S1	Mean PL1	Mean S2	Mean PL2	Mean S3	Mean PL3	Agg. RT	Agg. PL
EXP001	26	Thai	1	1	1	1	4	1	5	2	5	4	5	4	2	2	3	2	2	2	1.5	3.5	3.5	3	2.5	3.5	2.500	3.333
EXP003	25	Spanish	3	5	4	5	4	1	2	5	4	2	4	4	2	4	4	3	4	4	1.5	3.5	3	3	4.5	4	3.000	3.500
EXP004	26	Indian	4	3	4	5	5	2	4	4	3	4	2	5	2	5	3	2	5	4	2	2.5	4.5	4.5	3.5	3	3.333	3.333
EXP005	28	Brazilian	5	5	5	4	4	4	4	3	1	1	1	4	3	5	2	3	4	2	3.5	2	4.5	2.5	2.5	1.5	3.500	2.000
EXP006	36	Colombian	5	5	5	5	5	1	5	4	2	5	2	5	2	5	5	3	5	3	1.5	2.5	5	5	4.5	2.5	3.667	3.333
EXP007	36	American	5	5	5	5	3	1	2	4	1	2	4	3	1	4	2	1	4	1	1	1	3	3	3	2.5	2.333	2.167
EXP009	25	Colombian	4	3	3	3	4	1	5	2	1	4	4	4	1	2	1	1	2	4	1	1	3.5	3	1.5	4	2.000	2.667
EXP010	34	Greek	1	1	1	2	5	3	5	4	2	5	4	5	2	5	5	3	5	3	2.5	2.5	5	5	4.5	3.5	4.000	3.667
EXP011	24	Colombian	4	2	3	4	2	1	4	3	5	3	4	2	1	4	2	1	2	3	1	3	4	2.5	2.5	3.5	2.500	3.000
EXP012	23	Turkey	5	2	3	3	4	1	1	3	1	1	4	4	2	5	4	1	1	5	1.5	1	3	1	3.5	4.5	2.667	2.167
EXP013	30	Ecuador	2	3	4	4	4	5	1	3	3	5	2	4	5	5	4	2	5	2	5	2.5	3	5	3.5	2	3.833	3.167
EXP014	24	Turkish	2	1	2	3	4	1	4	3	2	4	1	4	3	4	2	3	4	3	2	2.5	4	4	2.5	2	2.833	2.833

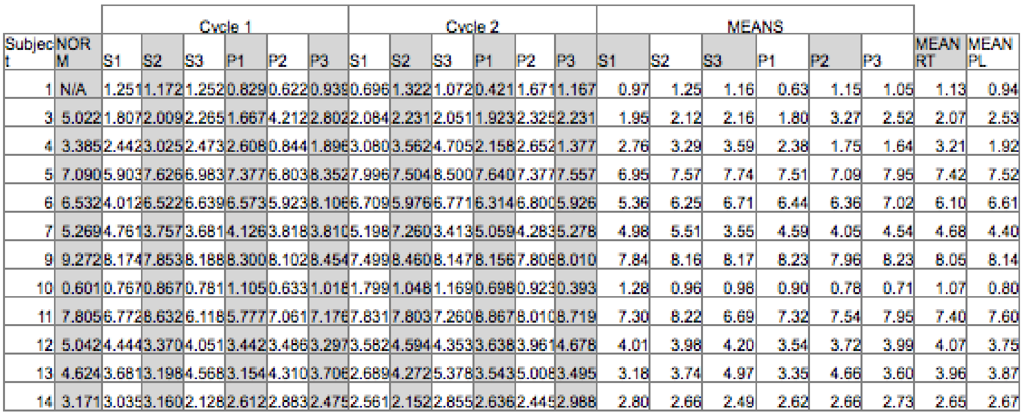
Relaxation State:

								Cycle 1							Cycle 2													
ID	Age	Nationality	Ability_Gen	Composition	Ability_Elec	Understanding	Relaxation_Init	S1	S2	S3	PL1	PL2	PL3	Relaxation_Interval	S1	S2	S3	PL1	PL2	PL3	Mean S1	Mean PL1	Mean S2	Mean PL2	Mean S3	Mean PL3	Agg. RT	Agg. PL
EXP001	26	Thai	1	1	1	1	4	2	5	2	1	1	4	4	1	3	1	1	1	5	1.5	1	4	1	1.5	4.5	2.333	2.167
EXP003	25	Spanish	3	5	4	5	4	4	5	3	3	4	4	4	4	4	4	5	4	5	4	4	4.5	4	3.5	4.5	4.000	4.167
EXP004	26	Indian	4	3	4	5	5	5	2	4	5	5	4	5	5	5	4	5	5	5	5	5	3.5	5	4	4.5	4.167	4.833
EXP005	28	Brazilian	5	5	5	4	4	4	4	3	3	4	4	4	4	4	4	4	5	3	4	3.5	4	4.5	3.5	3.5	3.833	3.833
EXP006	36	Colombian	5	5	5	5	5	3	4	4	3	5	5	5	4	5	5	4	5	4	3.5	3.5	4.5	5	4.5	4.5	4.167	4.333
EXP007	36	American	5	5	5	5	3	4	5	5	4	5	5	3	4	5	4	3	3	2	4	3.5	5	4	4.5	3.5	4.500	3.667
EXP009	25	Colombian	4	3	3	3	4	1	3	3	1	4	3	4	3	4	4	3	4	4	2	2	3.5	4	3.5	3.5	3.000	3.167
EXP010	34	Greek	1	1	1	2	5	4	5	4	4	5	4	5	4	5	5	3	5	4	4	3.5	5	5	4.5	4	4.500	4.167
EXP011	24	Colombian	4	2	3	4	2	3	3	3	3	3	3	2	2	2	2	3	3	3	2.5	3	2.5	3	2.5	3	2.500	3.000
EXP012	23	Turkey	5	2	3	3	4	3	5	4	2	5	3	4	4	4	3	2	4	4	3.5	2	4.5	4.5	3.5	3.5	3.833	3.333
EXP013	30	Ecuador	2	3	4	4	4	3	2	4	3	4	3	4	3	4	3	4	3	4	3	3.5	3	3.5	3.5	3.5	3.167	3.500
EXP014	24	Turkish	2	1	2	3	4	3	4	5	3	4	4	4	4	5	4	4	4	4	3.5	3.5	4.5	4	4.5	4	4.167	3.833

Appendix B

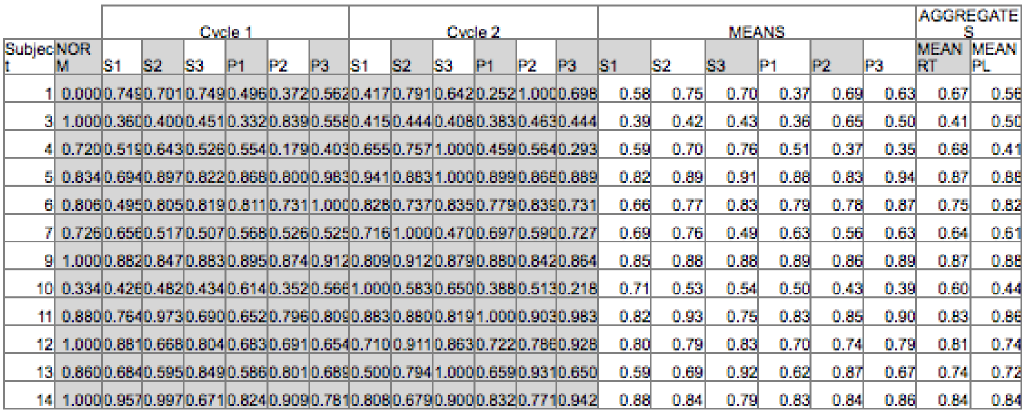
Physiological Data

Absolute Values:



		Cycle 1						Cycle 2						MEANS							
Subject	NORM	S1	S2	S3	P1	P2	P3	S1	S2	S3	P1	P2	P3	S1	S2	S3	P1	P2	P3	MEAN RT	MEAN PL
1	N/A	1.251	1.172	1.252	0.829	0.622	0.939	0.696	1.322	1.072	0.421	1.671	1.167	0.97	1.25	1.16	0.63	1.15	1.05	1.13	0.94
3	5.022	1.807	2.009	2.265	1.667	4.212	2.802	2.084	2.231	2.051	1.923	2.325	2.231	1.95	2.12	2.16	1.80	3.27	2.52	2.07	2.53
4	3.385	2.442	3.025	2.473	2.608	0.844	1.896	3.080	3.562	4.705	2.158	2.652	1.377	2.76	3.29	3.59	2.38	1.75	1.64	3.21	1.92
5	7.090	5.903	7.626	6.983	7.377	6.803	8.352	7.996	7.504	8.500	7.640	7.377	7.557	6.95	7.57	7.74	7.51	7.09	7.95	7.42	7.52
6	6.532	4.012	6.522	6.639	6.573	5.923	8.106	6.709	5.976	6.771	6.314	6.800	5.926	5.36	6.25	6.71	6.44	6.36	7.02	6.10	6.61
7	5.269	4.761	3.757	3.681	4.126	3.818	3.810	5.198	7.260	3.413	5.059	4.283	5.278	4.98	5.51	3.55	4.59	4.05	4.54	4.68	4.40
9	9.272	8.174	7.853	8.188	8.300	8.102	8.454	7.499	8.460	8.147	8.156	7.808	8.010	7.84	8.16	8.17	8.23	7.96	8.23	8.05	8.14
10	0.601	0.767	0.867	0.781	1.105	0.633	1.018	1.799	1.048	1.169	0.698	0.923	0.393	1.28	0.96	0.98	0.90	0.78	0.71	1.07	0.80
11	7.805	6.772	8.632	6.118	5.777	7.061	7.176	7.831	7.803	7.260	8.867	8.010	8.719	7.30	8.22	6.69	7.32	7.54	7.95	7.40	7.60
12	5.042	4.444	3.370	4.051	3.442	3.486	3.297	3.582	4.594	4.353	3.638	3.961	4.678	4.01	3.98	4.20	3.54	3.72	3.99	4.07	3.75
13	4.624	3.681	3.198	4.568	3.154	4.310	3.706	2.689	4.272	5.378	3.543	5.008	3.495	3.18	3.74	4.97	3.35	4.66	3.60	3.96	3.87
14	3.171	3.035	3.160	2.128	2.612	2.883	2.475	2.561	2.152	2.855	2.636	2.445	2.988	2.80	2.66	2.49	2.62	2.66	2.73	2.65	2.67

Relative Values:



		Cycle 1						Cycle 2						MEANS						AGGREGATES	
Subject	NORM	S1	S2	S3	P1	P2	P3	S1	S2	S3	P1	P2	P3	S1	S2	S3	P1	P2	P3	MEAN RT	MEAN PL
1	0.000	0.749	0.701	0.749	0.496	0.372	0.562	0.417	0.791	0.642	0.252	1.000	0.698	0.58	0.75	0.70	0.37	0.69	0.63	0.67	0.56
3	1.000	0.360	0.400	0.451	0.332	0.839	0.558	0.415	0.444	0.408	0.383	0.463	0.444	0.39	0.42	0.43	0.36	0.65	0.50	0.41	0.50
4	0.720	0.519	0.643	0.526	0.554	0.179	0.403	0.655	0.757	1.000	0.459	0.564	0.293	0.59	0.70	0.76	0.51	0.37	0.35	0.68	0.41
5	0.834	0.694	0.897	0.822	0.868	0.800	0.983	0.941	0.883	1.000	0.899	0.868	0.889	0.82	0.89	0.91	0.88	0.83	0.94	0.87	0.88
6	0.806	0.495	0.805	0.819	0.811	0.731	1.000	0.828	0.737	0.835	0.779	0.839	0.731	0.66	0.77	0.83	0.79	0.78	0.87	0.75	0.82
7	0.726	0.656	0.517	0.507	0.568	0.526	0.525	0.716	1.000	0.470	0.697	0.590	0.727	0.69	0.76	0.49	0.63	0.56	0.63	0.64	0.61
9	1.000	0.882	0.847	0.883	0.895	0.874	0.912	0.809	0.912	0.879	0.880	0.842	0.864	0.85	0.88	0.88	0.89	0.86	0.89	0.87	0.88
10	0.334	0.426	0.482	0.434	0.614	0.352	0.566	1.000	0.583	0.650	0.388	0.513	0.218	0.71	0.53	0.54	0.50	0.43	0.39	0.60	0.44
11	0.880	0.764	0.973	0.690	0.652	0.796	0.809	0.883	0.880	0.819	1.000	0.903	0.983	0.82	0.93	0.75	0.83	0.85	0.90	0.83	0.86
12	1.000	0.881	0.668	0.804	0.683	0.691	0.654	0.710	0.911	0.863	0.722	0.786	0.928	0.80	0.79	0.83	0.70	0.74	0.79	0.81	0.74
13	0.860	0.684	0.595	0.849	0.586	0.801	0.689	0.500	0.794	1.000	0.659	0.931	0.650	0.59	0.69	0.92	0.62	0.87	0.67	0.74	0.72
14	1.000	0.957	0.997	0.671	0.824	0.909	0.781	0.808	0.679	0.900	0.832	0.771	0.942	0.88	0.84	0.79	0.83	0.84	0.86	0.84	0.84

Appendix C

MATLAB Script Used for Physiological Data Analysis

```
EEG = pop_biosig('/Users/adityanandwana/Desktop/MATLAB EEG
working folder/S005/EXP005-C1-SN1.gdf'); // opens the GDF file
containing physiological data //

EEG.setname='S5C1SN1'; // Gives each session an unique name //

EEG = eeg_checkset( EEG ); // Check the consistency of the
fields of an EEG dataset //

EEG = pop_select( EEG,'channel',{'T7' 'P7' 'O1' 'O2' 'P8'
'T8'}); // Channel selection //

EEG = eeg_checkset( EEG );

EEG = pop_rmbase( EEG, [0 115000]); // Removal of DC offset //

EEG = eeg_checkset( EEG );

figure; [result_matrix f_matrix] = pop_spectopo(EEG, 1, [10000
115000], 'EEG' , 'percent', 100, 'freq', [], 'freqrange',[1
30],'electrodes','off'); // FFT, creation of a matrix storing
instantaneous power values for each frequency within 1-30 Hz of
the EEG spectrum //

alpha1 = mean (result_matrix(:, find(f_matrix >= 7 & f_matrix <=
13 )), 2); // Isolation of alpha band values from the frequency
matrix //

falphaC11 = mean (alpha1); // Calculation of mean alpha power
for the session, storing value to memory //
```