Sonification of EEG signals

A study on alpha band instantaneous coherence

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To my mother
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Abstract

This master project aims to study sonification techniques for the explicit display of Electroencephalography signals (EEG). In particular, this research focuses on studying the correlation between EEG signal characteristics and the information perceived through sounds. A system for real-time presentation of sound synthesis based on EEG measures was developed and experiments on sound perception and recognition were carried out. The primary goal of the study was to understand what sonification strategies led to a better display and subjective recognition of EEG signal dynamics. While the specific goals of the study were firstly to investigate the application of different sound mappings to display different EEG signal features, next to develop a sonification system that allowed auditory display of real-time and off-line EEG data and finally to assess the success of different EEG sonification techniques in providing the subjective experience of alpha band instantaneous coherence. Therefore, different sonification scenarios were created and submitted to subjects participating in experiments, during which their subjective assessments were acquired in real-time by physical inputs (midi controller). Then data were analyzed by means of correlation analysis in order to evaluate how subjects react to the induced auditory stimuli: the goal of the analysis was to find out how EEG features (coherence level) could be perceived among different sonification strategies. The correlation analysis has shown that the Hybrid sonification obtained the better results. It achieved an average correlation of \( r=0.7441 \) with \( p<0.005 \) and a maximum average value of \( r=0.8995 \). In general all sonification reached average correlation \( r \) values greater than 0.6 always with \( p<0.005 \). Furthermore, this project takes part of an ongoing research on Physiology-based Interaction for Computer-Supported Collaborative Performance [59] [60].
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1 INTRODUCTION

1.1 Problem Statement

The aim of this work is developing a sonification system that allows subjects to subjectively perceive EEG-channel pairs’ coherence by listening to a real-time sonification of such signals. Sonification is the discipline of data exploration by manipulating the data’s transformation into sound [1]. It presents information by using sound (particularly non-speech), so that the subject of an auditory display can obtain a deeper understanding of the data or processes under investigation by listening [1]. While auditory display techniques have been applied in different fields such as data-mining, exploration of complex data and EEG display, its application on the detection of instantaneous coherence between EEG channels and neurophysiologic synchronies in EEG patterns is still scarce.

The Electroencephalogram (EEG) is a neurophysiologic measurement of electrical activity produced by the brain. The brainwaves showed by EEG, are the visual plotting of the brain neural electric activities projected to the scalp surface [2]. In this work we focused on alpha band coherence between F3 and P4 EEG channels, according to the 10-20 system [35]. The coherence of two EEG waves follows from how well correlated the waves are as quantified by the cross-correlation function [52]. $C_{xy}(\omega)$ is a real function between 0 and 1 which gives a measure of correlation between $x$ and $y$ at each frequency $\omega$. The steps that led to the final implementation were also discussed; information gathered from early attempts were essential to design the final system. The signal processing was written in Matlab [51]. Next the data was sent to the sound engine that produces the auditory stimuli in order to investigate different sonification strategies. The synthesis patch consists in a Pure Data [55] implementation of highly scalable and configurable code for generating sounds and different mappings.

This study also introduces a new methodological approach to design EEG sonification experiments that confirms the hypothesis about the evidence of auditory display techniques. Moreover, it provides a framework for a reliable and objective evaluation of sonification strategies. The subject hearing the sonification, moves the physical slider according to the subjective EEG features perceived. In particular using the MIDI slider, subjects assess in real-time whether the signal instantaneous EEG coherence can be perceived subjectively from the generated sound.

The experiment consisted of three types of sonification based on variations in pitch, rhythm or hybrid which means both variations at the same time, which were tested with a sample of 12 subjects aged between 18 and 32 years. The goal was to find a sonification strategy that ensures that the EEG features be perceived as accurately as possible. To process the acquired information, a Matlab code for the statistical analysis was written: starting from the 12 logfile of each subject, were calculated the correlation
coefficients at the 5% significance level, for each of the 6 trials and for each of the 3 sonification techniques, for a total of 216 coefficients. Finally the analysis evaluates the discriminative power of auditory data display with different sonifications.

1.2 Sonification of EEG signals: State-of-the-art

This chapter first introduces general aspects of the brain anatomy, then an overview of the history and origin of the EEG. Next the chapter introduces definitions and present day techniques. Finally the chapter gives a summary of EEG and BCI systems today in use and the music application.
1.2.1 Bioelectromagnetic phenomena

1.2.1.1 Brain Anatomy

The brain (fig. 1) is the most complex part of the human body. It controls thought, memory, emotion, touch, motor skills, vision, respirations, temperature, hunger, and every process that regulates our body. The brain can be divided into the cerebrum, brainstem, and cerebellum [3].

The cerebrum is the largest part of the brain and is composed of the right and left hemispheres. Functions of the cerebrum include: initiation of movement, coordination of movement, temperature, touch, vision, hearing, judgment, reasoning, problem solving, emotions, and learning. More specifically four lobes make up the cerebrum, the frontal, temporal, parietal, and occipital.

![Fig. 1 The three main components of the brain are the cerebrum, the cerebellum, and the brainstem. The cerebrum is the largest and most developmentally advanced part of the human brain. [3].](image)

The frontal lobe is the largest section of the brain located in the front of the head. It controls attention, behaviour, abstract thinking, problem solving, creative thought, emotion, intellect, initiative, judgment, coordinated movements, muscle movements, smell, physical reactions, and personality.

The parietal lobe is the middle part of the brain, the parietal lobe helps a person to identify objects and understand spatial relationships between the person and objects around him/her. The parietal lobe is also involved in interpreting pain and touch in the body.

The occipital lobe is the back part of the brain and it is involved with the brain’s ability to recognize objects. It controls vision.

The temporal lobes are sited on both sides of the brain, they are involved in auditory and visual memories, language and in general are involved in the primary organization of sensory input [4].
1.2.1.2 The Electroencephalogram

The Electroencephalogram (EEG) is a neurophysiologic measurement of electrical activity produced by the brain through electrodes attached on the surface of the scalp. Its amplitude is about 100 μV when measured on the scalp and 1-2 mV when measured on brain surface [5]. EEG is also capable of detecting changes in electrical activity on a millisecond-level and it is one of the few techniques available that has such high temporal resolution. The first EEG recording of the electric field of the human brain was made by the German psychiatrist Hans Berger in 1924 (fig.2) [6]. Since the occipital area is most heavily involved in the processing of visual information from the eyes, the recording was subject to variation associated simply with opening and closing eyes.

Fig.2 The first EEG recording, obtained by Hans Berger in 1924. The upper tracing is EEG, and the lower is a 10 Hz timing signal. [6].
1.2.1.3 Rhythmic activity

In the EEG records, the classification of waveforms is made according to their frequency. Historically four major types of continuous and rhythmic sinus-like waves are recognized (α, β, δ and θ). There is no precise agreement on the frequency ranges for each type:

1) δ (delta) has a frequency of 4 Hz or below. It tends to be the highest in amplitude and the slowest waves. It is often seen frontally in adults during deep sleep but it may occur as a consequence of lesions. This is what delta waves look like [7]:

![Delta waves](image1)

2) θ (theta) is in the frequency range: 4 Hz ─ 8 Hz and is classified as "slow" activity. It is associated with drowsiness, childhood, adolescence and young adulthood. This EEG frequency can sometimes be produced by hyperventilation. θ waves can be seen during hypnagogic states such as trances, hypnosis, deep day dreams, lucid dreaming and light sleep and the preconscious state just upon waking, and just before falling asleep. Theta waves look like this [7]:

![Theta waves](image2)

3) α (alpha) is in the frequency range: 8 Hz ─ 12 Hz. It is the major rhythm seen in normal relaxed adults. It appears when closing the eyes and relaxing, and disappears when opening the eyes or alerting by any mechanism. Is usually best seen in the posterior regions of the head on each side and higher amplitude on the dominant side. An α-like normal variant called mu rhythm is sometimes seen over rhythm attenuates with movement of limbs, or mental imagery of movement. This is what alpha waves look like [7]:

![Alpha waves](image3)

4) β (beta) has a frequency of 13 and greater Hz. It is "fast" activity and is generally regarded as a normal rhythm. It is seen in low amplitude with multiple and varying frequencies symmetrically on both sides in the frontal area. It is often associated with active, busy or anxious thinking and active concentration. It may be absent or reduced in areas of cortical damage. This is what Beta waves look like [7]:

![Beta waves](image4)
1.2.1.4 Instantaneous EEG coherence

Neurophysiologic coherence in EEG patterns (fig.3) is considered to reflect the number and strength of connections between two different areas of the brain. Coherence has been applied to study team communication (as engagement and workload), convergent and divergent thinking (as creativity) and elementary comparison processing. All these works rely on visual display techniques. A work rely auditory display and EEG coherence was conducted by Nijboer et al. (2008). Feedback of the SMR amplitude was realized by either harp or bongo sounds [8]. SMR decoherence was represented by bongo sounds and coherence by harp sounds. That is, an auditory feedback based on triggering pre-recorded sounds and not on a real-time sound engine. Sonification application on the detection of instantaneous coherence between EEG channels and neurophysiologic synchronies in EEG patterns is still scarce.

Two EEG signals are considered synchronized if the waves have the same energy distribution. Mathematically, it is the absolute value of the cross-correlation function in the frequency domain of two electrical signals, but with frequency dependency. Coherence is very sensitive for number of epochs in analysis and their length. It is more stable when segments of many seconds are analyzed and intervals of the same length in different states are necessary to compare it.

Fig.3 EEG tracings recorded during practice of the TM technique (8 seconds). The lines are moving up and down together. Brainwaves are no longer scattered but "in phase," indicating that neurons are firing in harmony within the same alpha frequency. [9]
1.2.2 From bioelectricity to BCI: The history of the brainwaves sonification

1.2.2.1 Early studies

The history of the brainwaves research and in general the study of bioelectrical phenomena in animals or plants, starts around 1780 with Luigi Galvani. Galvani discovered that he could cause contraction in a frog’s leg muscles by applying an electrical current to exposed nerves. This work was followed by that of Emil Heinrich Du Bois-Reymond, considered the founder of modern electrophysiology, who in the 1840s began to measure biological currents in electric fish and later in humans via electrodes embedded directly in his own arm [10]. Toward the late of 19th century, the British neurophysiologist Richard Caton investigated the brain tissue spontaneous currents. In 1875 Caton reported the successfully measurements of brain electrical activity using electrodes implanted directly in the exposed cerebral hemispheres of rabbits and monkeys. It represents the very first recognized demonstration of the electrical brain’s activity. But at the time, it was not believed to be possible to extract meaningful measures by more non-invasive methods, as placing electrodes on the scalp. [10] In 1912 Vladimir Vladimirovich Pravdich-Neminsky, a Ukrainian physiologist, recorded a EEG from a dog on photographs. He also coined the term electrocerebrogram.

In 1920 Alexander Forbes, replaces string galvanometer with a vacuum tube to amplify EEG’s small electrical signal. This becomes the standard for EEG amplification. Forbes with his fifty-six years of active research, contributed over 100 publications to the development of the realm of neurophysiology [11]. Human brainwaves were first measured four years later, in 1924, by Hans Berger, at the time an unknown German psychiatrist. Five years after, in 1929 Berger publishes his brainwave results with the title Uber das Elektrenkephalogramm des Menschen (On the Electroencephalogram of Man). He reported the first single channel scalp recording of a human EEG from occipital region. He also publishes reports on intercortical activity and partial complex seizures. But the English translation of such work did not appear until 1969 [11].
1.2.2.2 The 30s’ : The EEG diffusion

In 1932, Jan Friedrich Tonnies develops the very first modern EEG for Hans Berger whose discovery of the “Electroencephalogram” was recognized worldwide two years later. It consists in multichannel ink-writing EEG machine, with its moving paper and vibrating pens. Together with Brian Matthews he also designed one of the first differential amplifiers that same year before he spent three years at the Physiology lab of H. S. Gasser who was the director of the Rockefeller Institute for Medical Research at that time. Donald B. Lindsley, co-founder of UCLA’s Brain Research Institute, was pioneer in the study of human brain waves. Lindsley was one of the first scientists to use the newly discovered technique of electroencephalography to record electrical brain activity.

During his postdoctoral studies with Alexander Forbes and Hallowell Davis at Harvard University (1933-35), Lindsley himself served as the subject for the premier public demonstration of EEG to the American medical community. Initially, Berger’s work was largely ignored. It was not until five years after his first paper was published [10], when his results were verified by the pioneering physiologists E.D. Adrian and B.H.C. Mathews, that his discovery began to draw attention. In their 1934 article in the journal Brain, Adrian and Matthews also reported the successfully attempt to sonify the measured brainwave signals which they had recorded according to Berger’s methods. While listening to his own alpha presented through a loud speaker, Adrian tried to correlate his subjective impression of hearing the alpha come and go with the activity of looking or not looking with his eyes. This was the first example of the sonification of human brainwaves for auditory display [13].

The same year (1934) Fisher and Lowenback demonstrate the first spikes on an EEG due to epileptic events, Ralph Gerard and Franklin Offner develop concentric needle electrodes and develop EEG equipment and Dr. Frederic Gibbs won a small grant to develop instrumentation to process electroencephalographic data. His goal was to apply the knowledge gained by Hans Berger and confirmed by Lord Adrian to clinical applications. In 1935 Gibbs approaches Albert Grass, a recent graduate of MIT, to design three devices to amplify human EEG potentials. Grass designs moving coil galvanometers, which enables the embryonic EEG instrumentation to accurately and reliably record the EEG frequencies on chart paper. The addition of these new galvanometers to his early amplifiers becomes the Grass Model I (fig. 4), used by Gibbs, Lennox, Davis and others. In 1936 the first EEG laboratory is founded at Massachusetts general hospital.
1.2.2.3 Post-war activity

In 1945, Albert Grass, who first built his 3–channel EEG machine at the Harvard Medical School, formed the Grass Instrument Company. This was for many years the leading supplier of EEG machines around the world, and its provision of reliable instruments allowed a rapid advance in the clinical application of EEG. Two years later, in 1947, The American EEG Society was founded and the first International EEG congress was held. In most of early EEG studies, scientist as H.W. Shipton (1949), V.J. Walter and W.G. Walter (1949), J. Corriol and H. Gastaut (1950), M.G.T. Hewlett (1951), E.C. Turton (1952) reported various methods of generating stimulus in the auditory domain that in some way followed brain rhythm frequencies. In 1949 H.W. Shipton designed an electronic trigger circuit suitable for investigating how feedback plays an important part in the analysis of human behaviour through the use of external stimuli as a means of evoking waveforms of clinical importance. However, in these works only the amplitude of the alpha waves or other simple and direct characters of EEG signals was utilized as the driving sources of the musical sound [14].

Up to that time, signal processing was done with analog systems, often using electronic circuits or mechanical devices, but since the 50's digital computers were begun to use to simulate signal processing systems, before implementing in analog hardware. It was a cheap way to vary parameters and test system output. In 1954, Robert Frances attempt to measure physiological concomitants of formal musical perception through polygraph readings, including EEG, GSR, heart rate and respiration rate while subjects listened to carefully selected musical examples [15]. Frances was able to use variations in polygraph readings, associated with alpha brainwave blocking, to differentiate among subjects with more or less musical training, subjects instructed to listen actively versus passively, and subjects instructed to listen with an analytical versus a spontaneous attitude. In the late 1950’s, Joe Kamiya studied the phenomenon of internal perception or the awareness of private internal experiencing. Accidentally he discovered that a subject could learn through feedback to reliably discriminate between alpha and beta dominant cortical states, and then further demonstrated that a subject
could learn to produce such alpha or beta brain states on demand [16]. In 1958 Jasper
leads a committee to standardize the EEG 10/20 system of placing electrodes on the
scalp [17].

1.2.2.4 The 60s’ and the 70s’

In 1961, Neal Miller of Rockefeller University in New York, first suggested that
the autonomic nervous system could be as susceptible to training as the voluntary
nervous system, that people might learn to control their heart rate and bowel
contractions just as they learned to walk or play tennis [18]; the biofeedback paradigm
began to be clearly articulated and became widely known during all the 60s. Digital
signal processing also started to become a discipline and although its roots go much
further back. This made it possible to predict that traditional analog processing devices
such as filters and spectrum analyzers would become digital and result in big
improvements for many applications. In 1965 Cooley and Tukey discover efficient
algorithm for Fast Fourier Transforms (FFT). That made feasible real-time signal
processing as well as algorithms previously thought impossible to implement on digital
computers. The follow year, 1966, Goldensohn assembles first closed circuit television
EEG recording system. Finally automatic data processing becomes prevalent within
EEG signal processing.

The 1965-1975 decade was definitive and formative for digital art precisely
because the technology was new and in rapid transition, as well as, the imaginations and
aspirations of the artists. The use of brainwaves to generate music did not occur until
1965. Alvin Lucier had begun working with physicist Edmond Dewan in 1964,
performing experiments that used brainwaves to create sound. The next year, he was
inspired to compose a piece of music using brainwaves as the sole generative source.
Music for Solo Performer achieved a direct mapping of a soloist's alpha: amplified
alpha signals were used to activate, either acoustically or mechanically, an array of
percussion instruments. It was presented, with encouragement from John Cage, at the
Rose Art Museum of Brandeis University in 1965 [10][19]. In 1967, Edmond Dewan
described experiments using subjects wired to an EEG device, which records and graphs
the electrical activity of the brain. With practice, the subjects were able to reduce the
amplitude of their brains' alpha rhythms, to transmit Morse code to a teleprinter.

In the late 1960s, Richard Teitelbaum was a member of the innovative Rome-
based live electronic music group Musica Elettronica Viva (MEV). In performances of
Spacecraft (1967) he used various biological signals including EEG and ECG signals as
control sources for electronic synthesizers. Organ Music and In Tune, both realized in
1968, added heart beat and breath sounds, sensed with contact microphones, to EEG
signals in the creation of an electronic music texture [20]. Over the next few years,
Teitelbaum continued to use EEG and other biological signals in his compositions and
experiments as triggers for nascent Moog electronic synthesizers [10].
Simultaneously, Manfred Eaton, another early experimenter, carried out experiments in music and bioelectric phenomena at the ORCUS Research Center in Kansas City. Eaton described the application of various biosignals to artistic projects in order to study the aesthetic responses to the stimuli. He initially published an article titled Biopotentials as Control Data for Spontaneous Music (Orcus) in 1968 [21]. In that summer, Erkki Kurenniemi visited an electroacoustic music conference organized by Teatro Comunale in Florence, Italy. During the conference Kurenniemi was introduced to Eaton’s ideas of biofeedback as a source of musical or compositional material. Two of Kurenniemi’s instruments Dimi-S and Dimi-T, are based on these ideas. Dimi-T where T stands for thinking, was developed in 1973; it used alpha waves produced by the human brain while sleeping for controlling the pitch of an oscillator.

In October 1969 the Biofeedback Research Society was formed, held its first meeting in Santa Monica, and the phenomenon of biofeedback officially received its name. One year later, Rosenboom starts to experiment in musical production using alpha rhythms and explorations of the relation of alpha wave production to music perception. In Ecology of the Skin (1970), an environmental demonstration-participation performance, Rosenboom used brainwaves and heart signals from performers and audience members and their translation into a musical texture, to explore the various states of awareness and consciousness associated with music performance [22]. In 1971, the French scientist Roger Lafosse and the music pioneer Pierre Henry proposed a sophisticated live performance system known as Corticalart (art from the cerebral cortex). In a series of free performances done in 1971, Henry in dark sunglasses with electrodes hanging from his head, projected the content of his brainwaves changed the colour of the image according to his brainwave variations [10]. The same year, Eaton first published his manifesto Bio-Music: Biological Feedback Experiential Music Systems.

In the 70’s early BCI research was also started, Professor Jacques J. Vidal first introduced the idea of direct brain computer communication. In his BCI Laboratory at the University of California Los Angeles (UCLA), under a grant from the National Science Foundation, a successful project demonstrated that a computer-generated visual stimulation is able to evoke people to produce a certain response which could provide a communication channel between the subject and a computer. In 1973, he published Toward Direct Brain-Computer Communication [23], this research also mark the first appearance of the expression brain–computer interface in scientific literature. The Advanced Research Projects Agency (ARPA) also tended to develop similar communication systems driven by brainwaves for use in military applications. The aim was to improve the performance of military personnel especially in tasks involving heavy mental loads, the investigation produced valuable insights but, due to the technological, it made minimal progress toward its goals [24]. Around the same time, Rosenboom founded the Laboratory of Experimental Aesthetics at York University in
Toronto, where pioneering collaborations between scientists and artists was encouraged. The laboratory undertook experimentation into the artistic possibilities of brainwaves and other biological signals in cybernetic biofeedback artistic systems [10]. Many artists and musicians visited and worked at the facility during this time including John Cage, David Behrman, LaMonte Young, and Marian Zazeela. Some of the results of the work at this lab were published in the book Biofeedback and the Arts (Aesthetic Research Centre of Canada, 1976). Parallel to the research in Toronto, the Montréal group SONDE, along with Charles de Mestral, did some brainwave performances. At Logos in Ghent, Belgium, real-time brainwave triggered concerts were presented in 1972 and 1973. In Baltimore the Peabody Electronic Music Consort did performances. Rosenboom and others continued their work at Mills College [10].

Toward the end of the 1970s, biofeedback and brainwave research fell into a period of quiescence due to many factors, primarily a lack of funding and of sufficiently powerful computers and secondarily because the scientific community became increasingly sceptical. Ancoli and Kamiya (1978) critiqued the methodological weaknesses and inconsistencies of many of the early studies on alpha feedback training. They found the quality and length of training inadequate in many studies, and criticized researchers for neglecting to monitor such critical variables as the social interactions between experimenter and subject, and instructional set. In 1979 Basmajian declared that “Alpha feedback is still a mystery but it is not an acceptable treatment method”. For about ten years, almost nothing happened in the field [10].
1.2.2.5 From the 90s’ to the nowadays

During the 1980’s numerous IC technology advancements, as fixed-point and floating-point microprocessors for digital signal processing and in general though computing capabilities diffusion in nearly every electrophysiology laboratory, were sufficient to allow advanced signal processing. Digital EEG becomes prevalent and topographic mapping makes EEG popular in a variety of clinical fields. Kamiya’s work on voluntary production of alpha states coincided with the dawning counter-cultural interest in altered states of consciousness, and the emergence of a new interest in Eastern religions, the psychology of consciousness, and in transpersonal psychology (Moss & Keen, 1981; deSilva, 1981). Cleve Barry Moler, a mathematician and computer programmer, invented Matlab a numerical computing package. Recognizing its commercial potential, in 1984 he co-founded MathWorks with Jack Little, to commercialize and to continue its development. Matlab was first adopted by researchers and practitioners in control engineering, but quickly spread to many other domains. It is now popular amongst scientists involved in signal processing and numerous toolboxes were developed for EEG analysis. In that decade, pioneer researchers also tried to apply to EEG data analysis techniques developed in electrical engineering and information theory, including time/frequency analysis and Independent Component Analysis (ICA). These techniques revealed EEG processes whose dynamic characteristics are also correlated with behavioral changes, events that cannot be seen before due technical limitations that constrained researchers to confine their EEG data analysis [25].

In 1990, real time digital EEG monitoring is standard. The availability of fast and low-cost digital computers and the improvements in signal processing algorithms allow EEG to be used in the field of cognitive neurosciences as a subject of research. The same year, U.S. President George Bush declares the decade starting in 1990 the "Decade of the Brain". Benjamin Knapp and Hugh Lusted, began working on a computer interface called the BioMuse [26]. It permitted a human to control certain computer functions via bioelectric signals including EEG and EMG. In 1992, Atau Tanaka [27] was commissioned by Knapp and Lusted to compose and perform music using the BioMuse as a controller. Tanaka continued to use the BioMuse, primarily as an EMG controller, in live performances throughout the 1990s [10]. In 1996, Knapp and Lusted wrote an article for Scientific American about the BioMuse called Controlling Computers with Neural Signals [28].

In the early 2000s there has been a renewed interest in brainwave music and a resurgence in its performance. In 2001, Neam Cathode at Montreal’s Oboro Gallery showed Cyber Mondrian [29] a work that incorporated Mondrian-like generated images with synthesized sound that was controlled using the Interactive Brainwave Visual Analyzer (IBVA) system. The same year, Andrew Brouse, created his InterHarmonium [30] an internet-enabled brainwave performance system based on Max/MSP [56] and
OpenSoundControl [57]. In 2002 David First created OPERATION: KRACPOT [31] using “brainwave entrainment” and the phenomenon of the Schumann resonances to create haunting music. In 2003, James Fung and Steve Mann prepared an improvised collective musical piece created interactively from the brainwaves of audience participants. The Regenerative Brainwave Music (REGEN3) was orchestrated by feeding tiny micro-voltages gathered from forty wired performers into a responsive EEG network: a “cyborg collective” comprising the cybernetic interactions between performers, musicians, electronics, and computing machines [10]. Adam Overton, a student of David Rosenboom at CalArts, performed his series of works entitled Sitting. Breathing. Series and Other Biometric Work [32].

Many other artists utilized brainwaves for musical purposes, a Montreal group made up of Pierre Droste, Andrew Culver and Charles de Mestral, and also Janez Janša who developed Brainscore and led the project Brainloop. Even an underwater brain concert has been performed during the ICMC 2007 using an electroencephalophone [58]. Much of this new work was naive in the sense that the musicians were not fully cognisant of the rich history of brainwave music and research which has preceded them [10]. There has also been something of a bifurcation between those using hobbyist “biofeedback” equipment or techniques and those preferring to take a more rigorous “scientific” approach [10].

Over the past decade, also BCI research has grown rapidly and become a very popular research topic around the world. There are several active BCI research groups at universities, including the University of British Columbia, the Wadsworth Centre in Albany, the Berlin BCI group, a joint venture of several German research organisations, the University of Tübingen always in Germany; the Wadsworth Center in US and the Graz BCI research in Austria. At Neuromusic lab (University of Plymouth), Eduardo Miranda runs numerous researchers on brainwave music using Brain-Computer Interfaces [33].
1.2.3 EEG Technologies and Sound production

1.2.3.1 EEG Systems

An EEG system is a communication system that contains several parts: EEG input sensors, signal processing and output. The raw EEG sequences are digitized at a sampling rate of several hundred Hz as input data. The signal processing component is responsible for extracting appropriate features that encode the information, such as voltage amplitude measurements and spectral analysis. The signal features can be in the time or the frequency domain (rhythms amplitudes). Such system may also use both time-domain and frequency-domain signal features together to improve performance. Most EEG output devices are a computer screen. While the interest in systems based on an auditory display is growing.

1.2.3.2 Electrodes and the 10/20 system

To achieve a good record of EEG signals is important to select the appropriate type of electrodes for the measurement. The recording of these activities is obtained by placing electrodes on the scalp, usually after preparing the scalp area by light abrasion and application of a conductive gel to reduce impedance [34]. Electrodes that make the best contact with a subject’s scalp and contain materials that most readily conduct EEG signals provide the best EEG recordings. Nowadays dry electrode has the advantages of no need for skin preparation or conductive paste, but at the cost of less sensitivity and a weaker signal-to-noise ratio.

Fig.5 The letters used are: F Frontal lobe, T Temporal lobe, C Central lobe, P Parietal lobe, O Occipital lobe.
Electrode placement is determined by measuring and marking the scalp using a system called the 10-20 System of Electrode Placement (Fig.5). This system is a method used to ensure a system of placement that is reliable and reproducible [35]. The “10” and “20” reflecting the actual distances between adjacent electrodes are either 10% or 20% of the total front-back or right-left distance of the skull. The positions are determined by the following two reference points: nasion, which is the point between the forehead and the nose, level with the eyes; and inion, which is the bony prominence at the base of the skull on the midline at the back of the head. From these points, the skull perimeters are measured in the transverse and median planes [36]. Each site on the scalp has a letter to identify the lobe and a number to identify the hemisphere location. The letters F, T, C, P and O stand for Frontal, Temporal, Central, Parietal and Occipital respectively. A "z" (zero) refers to an electrode placed on the midline. While even numbers denote the right side of the head and odd numbers the left side of the head. When the EEG record need more detailed with the insertion of more electrodes, extra electrodes are added using the spaces in-between the existing 10-20 system.
1.2.3.3 Artifacts

Electrodes used in EEG recording, do not discriminate the electrical signals that they receive. The recorded activity which is not of cerebral is called artefact and in many cases the information that is hidden behind are relevant. An artifact may occur at many points during the recording process and it can be of two kinds: physiologic, arising from sites other than the brain (i.e. muscles, heart etc) and extra physiologic, that is generated outside the body (i.e. from environment and equipment). Elements such as the location, size, and function of the cortical area generating a rhythm or an evoked potential can indicate how the signal should be recorded and how to recognize and eliminate the effects of physiologic artifacts [7].

Recognition and elimination of artifacts is a big challenge. Types of common artifacts include: movement, sweating, ECG, eye movements (subject related) as well technical artifacts (50/60 Hz artifact, cable movements, electrode paste-related), which have to be handled differently. By looking at different parameters on a monitor, interference may be found.

Eye movement and blinks are the major physiological artifacts (fig.6), they produce electrical potentials and electro-magnetic fields that are often much larger than those deriving from brain sources. They can cause big errors in peak measurement or source localization. Furthermore blink artifacts frequency content, is negligible in the alpha band. Other artifacts, such as muscle activity, power line noise, body movements can also generate potentials that may even mimic cerebral activity.
1.2.3.4 Some perception issues

Detectability of a tone: Duration

The auditory system requires a stimulus about 300 milliseconds duration for maximal performance, if the duration is between about 10 and 300 milliseconds, its energy must remain approximately constant for a constant level of detection by the observer. Otherwise for duration of 300 milliseconds or longer the power must be held constant, whereas for durations shorter than 10 milliseconds, much more energy is required for tonal detection because short-duration tones are affected by spread of energy [37].

Just-Noticeable Sound in Frequency

Musical tones are rarely sinusoidal tones; they comprise many harmonic components and the frequency changes of these high-frequency harmonics can be more easily detected than frequency changes of the fundamental [41]. Pitch is highly correlated with frequency. In many instances listeners report perceiving a pitch in the absence of any energy at the frequency that corresponds to the reported pitch. That pitch processing is sometimes dependent neither on spectral information at the frequency of the pitch nor on periodicity information associated with the period of the pitch. Such audio paradox is known as the missing fundamental effect [38].

Temporal Masking

The study of masking is concerned with the interaction of sounds, the amount of interference one stimulus can cause in the perception of another stimulus. There are many acoustical events in which two stimuli follow one another in time. When the signal precedes the masker in time, the condition is called backward masking; when the signal follows the masker in time, the condition is forward masking. Forward masking of a stimulus can take place when temporal difference between the two stimuli is as much as 75 to 100 milliseconds, and backward masking occurs up to 50 milliseconds separation. These temporal masking data provoke interesting questions concerning how the nervous system might be encoding temporal events. [39]

Temporal separation: streaming

In many situations the sound from one source alternates with that from another source, yet we are more likely to perceive the sound as two sources occurring together at the same time rather than one source with an alternating percept. Under the proper stimulus circumstances, listeners describe the stimulus as if there are two concurrent sounds each with a distinct pulsating pitch, rather than one sound that alternate in pitch. The perception of the two alternating tones is two "streams of sound" running concurrently as if they were two sound sources, rather than one sound source that has an alternating pitch. Understanding the conditions that lead to stream-fusion and stream segregation is important for understanding how we determine the sources of sounds in multisource acoustic environments [40].
1.2.3.5 Sonification methods and techniques

Sonification of EEG data is a means of assisting and accelerating data inspection, pattern classification and exploratory data analysis. It is involved with the generation of artificial sounds using control by data or by parameters extracted from the data. A simple example is the “beeping” that indicates individual heartbeats during surgery to monitor the stability of a patient’s condition [42]. We define Interactive Sonification as “the discipline of data exploration by interactively manipulating the data’s transformation into sound”. The human auditory system in fact is able to distinguish sounds in a complex superposition and should thus be particularly suited for data mining and data exploration of multivariate data sets [43]. This use of auditory translations of EEG patterns allowed observers and investigators to employ the considerable integrative powers of auditory perception and feature extraction to guide them toward some insight into the form of these signals [22].

In general, these techniques may be classified into two categories [44]: the first one is sonification, which aims at monitoring the brainwaves in an auditory way and includes various methods, such as the direct parameter mapping [42]; the second one is the application of brainwave music in Brain Computer Interface which has involved musical theories in composition [45]. EEG music generation is based on very complex mapping rules, basic music esthetic theories are also considered. But to keep a proper balance between the science and art, only important principles of music were involved in the sonification. Different kinds of mapping can be also applied: in audification the voltage EEG measurement is translate into sound: it allows to detect outliers and rhythmical and pitched patterns in the raw signals. In Spectral Mapping Sonification, parameters are extracted from EEG (i.e. Power Band, Main Frequency, Magnitude) and the activity in a specific spectral band can be explored. The Distance Matrix Sonification focus on the coherence of different brain areas as a function of time.

Some of the most important authors in the field are Hermann, Baier and Hinterberger. Baier explores techniques to sonify rhythmic activity of epileptic seizures as measured by human EEG. In epileptic EEG the extrema of the time series (min and max) are natural candidates for “events”. This technique provides an efficient way to distinguish normal from abnormal rhythms [46]. Hermann investigates how an event based sonification can be informative in terms of auto- and cross-correlations of the multivariate data. He develops a method to create event-based rhythms from multivariate human EEG: the event-based sonification is an appropriate strategy to deal with multivariate time series of spatio-temporal physiologic patterns [47]. Finally Hinterberger in a recent work (2011) develops the Sensorium, a neurofeedback environment that allows people to experience signals from their body processes visually and auditorily. It is based on a parametric orchestral sonification, based on rhythm, pitch and amplitude. Each EEG Band is assigned to a different voice (timbre) of a MIDI device. Rhythms and frequencies are projected as soundscapes [48].
2 PROJECT DEVELOPMENT

2.1 Preliminary attempts

In this section we discuss the steps that led to the final implementation. In the first stage, a wide review of sonification techniques was conducted in order to develop a system for real-time presentation of sound synthesis based on the explicit representation of EEG signals. The digital signal processing code was written in Matlab. Also early tests on physiological signal acquisition were performed with the Enobio interface [49]. During the tests, Enobio has proven to have a weak real-time signal reliability, which affected the experiment design evolution on how carry on experiments on sound perception and recognition.

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In the second stage, many of the original considerations were abandoned. The design was improved passing to an off-line experiment: all the subjects would listen the same pre-recorded EEG tracks. Using the same stimulus would allow us to obtain more robust results. In this level, Enobio was used only to record the EEG tracks. Without the need to wear the sensors to the subjects, the time of each experiment session would be significantly reduced. Also Matlab code was improved including feature extraction as band separation (Alpha, Beta, and Theta), main frequency detection, power band and magnitude evaluation. For a more user-friendly interaction, a graphic user interface was also written in Processing [50] (fig.7). At this point the evaluation method would consist on three different sonification strategies (variation on pitch, rhythm and amplitude) each mapping implying three different EEG features, one at a time, for a total of 9 combinations. The experiment would have required to draw or to select a graphic plot, which matches the sonified signal feature. Answer ratio (corrects/wrongs) and time responses, would be used as parameters to estimate the best sonification strategy. With the first sonification tests, were realized that EEG recordings made with the ENOBIO were unsuitable. Such device is limited only to the frontal areas where the alpha rhythms are weaker. Furthermore deeper considerations on the method led to the need for a new paradigm for the experiment.
In the third stage, fine EEG recordings coming from the occipital region were selected. A data set of pairs of EEG signals came from the channels F4 and P3 of the same subject, was built. So that, the level of coherence of the two EEG channels, was different for each EEG pair. The evaluation method evolved by asking the subjects to assess in real-time the changes in coherence, moving a physical slider. At first, it was planned to sonify the two EEG channels, with two different sound stimuli at the same time. Next, a totally new sonification strategy, based on frequency modulation synthesis was designed. In both strategies was present the problem of presenting a sound stimulus, easy to discriminate.

Finally to reach a better comprehension of the mechanisms of sonification and to understand what kind of auditory stimuli present, a low-level study were conducted. Deeper studies on auditory perception, led to the final implementation.

2.1.1 EEG signal acquisition tests

The EEG signal acquisition was handled thought Starlab’s Enobio, a wearable, wireless and modular EEG sensor device (fig.8). The system features 4 channels with a sample rate of 250 Hz, and a dynamic range of 16-bit. The signals acquired were firstly amplified and streamed via IEEE802.15.4 PHY to a server application running in a local host for data display, next were sent to Matlab via TCP/IP. Enobio permits real-time EEG signal acquisition, without the need of any skin preparation or application of electrolytic gel. It is also a fast setup wireless device. It has to be placed in the frontal lobe, and electrodes can be easily adjusted using a headband. During the tests one electrode placed in the Frontal midline (Fz) lobe, was used to make the EEG signal acquisition. At first, real-time configuration was abandoned because weak real-time signal reliability: biofeedback effects could have affected the EEG signal and thus, the evaluation of the best sonification strategy. Next tests with early sonification engine proven, due to the weakness of alpha rhythms in the frontal areas, that also off-line EEG recordings were unsuitable because too unstable to be able to discriminate signal evolution through sound. State-of-the-art EEG recordings were chosen, as will be described below in the final implementation section.
2.1.2 EEG signal processing

The digital signal elaboration was conducted in Matlab. It has implemented numerous mathematical functions and it also provides instant access to several graphics functions. There are four ways of writing code in Matlab. The M-file method was used to create a script for digital signal analysis and processing; when the file is run in the workspace, the script is carried out. Moreover to make the real-time tests, it was possible to interface the written code in Matlab, via TCP/IP protocol, with ENOBIO acquisition software. To make digital signal analysis and processing (fig.10), at first, data have to be converted into the frequency domain. EEG raw data coming at a samples rate of 250 Hz from the Enobio device were processed in order to analyse the data signals for their frequency content. The spectral analysis separates the relative contribution of the different frequencies in the signal. The signal was processed in blocks of 256 samples each block was multiplied by a Hann window function of the same size. An FFT with a size of 256 samples is then performed; such elaboration, by selecting and discarding frequency components, was able to compute the power spectrum within particular frequency bands; that is to discriminate the three bands of interest. For each frequency band and for each time step, three features were extracted: band power, magnitude and main frequency. The resultant frequency bins were used to calculate signal spectrum which shows a distribution of magnitude values as a function of frequency. In the frequency domain, the band power is the square of FFT’s magnitude, while the main frequency within a define band, was calculated at each step, as the frequency in which the magnitude was maximum.

Fig. 10 The block diagram shows the EEG elaboration in order to extract the three desired features.
2.1.3 Early sonification strategies

In this section is presented the sound engine for real-time presentation of sound synthesis based on EEG features. A Pure Data implementation of highly scalable and configurable code for generating sounds and different mappings was developed in order to investigate different sonification strategies.

Spectral mapping sonification

The first sonification strategy was a spectral mapping sonification consisting on three parameters in which the three different sonification patches: pitch, rhythm and amplitude; each mapped the three EEG features extracted from Alpha Rhythms (power band, main frequency, magnitude) one at a time, for a total of nine conditions. When one condition was active, the other two sound parameters followed a constant behaviour. The sound behaviour of other frequency bands as Beta and Theta, was also investigate.

<table>
<thead>
<tr>
<th>POWER BAND</th>
<th>PITCH</th>
<th>RHYTHM</th>
<th>AMPLITUDE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Condition 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Condition 3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAIN FREQUENCY</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Condition 4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Condition 5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Condition 6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAGNITUDE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Condition 7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Condition 8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Condition 9</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Tab.1 Table of the different sonification conditions.

Testing such sonification by adding two sounds at the same time, one for each EEG channel was concluded that subjects would be exposed to a very complex task.
Frequency modulation sonification

As second sonification strategy, in order to reach a sonification that would allow perceiving the "similarity" or "resonance" between two EEG channels, was decided to apply a sonification with a single audio outcome for both EEG channels (F3 and P4).

For this purpose, frequency modulation (FM) synthesis was explored (fig.12). Currently no conducted researches were founded on the use of frequency modulation as a strategy of EEG sonification. Such technique involves a sine wave carrier whose instantaneous frequency is modulated, according to the waveform of the so-called modulator. That is has two parameters as input and only one as audio output. The timbre of a simple waveform is changed by frequency modulating it, with a modulating frequency that is also in the audio range, resulting in a more complex waveform and a different-sounding tone.

FM sonification proved to be a very promising technique, but not suitable for our purpose. It was seen that the FM sonification is very sensitive to small and slow variations of the two inputs, but in the case of two EEG channels, there are two inputs that changing rapidly and with a wide range of oscillation. Furthermore it was very difficult to produce a "pleasant sound" suitable for an experimental environment.
2.2 Final implementation

In this section the final implementation is discussed. Information gathered from early attempts were essential to design the final system (fig.14). It was opted for a low level approach and three sonification strategies that used a series of auditory stimuli that were the simplest possible, were developed. The aim of such interactive sonification was to allow subjects to subjectively perceive EEG-channel pairs’ objective coherence by listening to a real-time sonification of such signals. When looking at subjective coherence, we should aim at providing subjects with an auditory cue that represent at some extent the dynamic changes on objective coherence between EEG signals, but releasing the subject from making such calculation from a huge cluster of audio data (two sounds). This being said, if we provide a single sound that responds to the correlation factor of EEG channels, the experiment will not assess subject's accuracy on identifying "similarities" between two sounds, but how effective is the provided sound for the subjective perception of the objective coherence. The Matlab code was rewrite to process the coherence of the two EEG channels. This paradigm was tested in an experiment where a set of EEG recordings coming from pair of channels with different levels of coherence were sonified; then they were presented to subjects to assess whether its instantaneous coherence could be perceived subjectively from the generated sound. Finally for each trial was calculated the correlation coefficient between objective coherence (EEG recordings) and the coherence level subjective (subjects’ assessment) perceived through auditory display.

Fig. 14 System design
2.2.1 EEG data processing

The EEG recordings used were acquired at 500Hz from the same subject with a non-invasive technique of surface EEG. The EEG signals came from two scalp electrodes (the site F3 and P4 of the brain), during different test conditions. This has led to the creation of a dataset of pairs of EEG channels with different levels of coherence in the alpha rhythms frequency band. The coherence of two EEG waves follows from how well correlated the waves are as quantified by the cross-correlation function. The cross-correlation quantifies the ability to predict the value of the second wave by knowing the value of the first. So coherence is the dependence of one signal on another in the domain of frequency. That is the compute of coherence makes the comparison of the two signals at each frequency value. Since the coherence is defined as:

\[
C_{xy}(f) = \left( \frac{|S_{xy}(f)|^2}{(S_{xx}(f)) (S_{yy}(f))} \right)
\]

Where:

- \( C_{xy}(f) \) is: the coherence of time-domain signals \( x \) and \( y \) at frequency \( f \)
- \( S_{xy}(f) \) is: the cross-spectrum of time-domain signals \( x \) and \( y \) at frequency \( f \)
- \( S_{xx}(f) \) is: the auto-spectra of time-domain signals \( x \) at frequency \( f \)
- \( S_{yy}(f) \) is: the auto-spectra of time-domain signals \( y \) at frequency \( f \)

This function is a measure of the extent of correlation between two signals at a specific frequency. Also, since the underlying spectral estimate uses a finite time-domain window, each coherence sample represents on the order of a "bin" frequency interval [54]. To calculate the coherence of two signals over the alpha range of frequencies (7-14Hz) was sufficient averaging all coherence values in this band. In fact the formula take into account the frequency distribution (energy at each frequency bin between 7 and 14 Hz) so it was possible taking the average in the range, as if there was only one frequency bin.
Calculating EEG alpha coherence

Matlab coherence function \( C_{xy} = \text{mscohere}(x, y) \) finds the magnitude squared coherence estimate \( C_{xy} \) of the input signals \( x \) and \( y \) using Welch's averaged, modified periodogram method. The magnitude squared coherence estimate is a function of frequency with values between 0 and 1 that indicates how well \( x \) corresponds to \( y \) at each frequency. The magnitude squared coherence is a function of the power spectral densities \( (P_{xx}(f) \text{ and } P_{yy}(f)) \) of \( x \) and \( y \) and the cross power spectral density \( (P_{xy}(f)) \) of \( x \) and \( y \) [52]. Coherence is performed on the FFT of the two signals. FFT uses a finite time-domain window of 2000 samples that correspond to a 2 seconds length signal, with a hop-size of 256 samples. We obtain a new coherence value each 64 milliseconds, that is Matlab processed about 32 blocks per second. Finally the averaged value of coherence in the alpha range is sent to Pure Data sound engine at each time step.

<table>
<thead>
<tr>
<th>LEVEL OF COHERENCE</th>
<th>MIN</th>
<th>MAX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Very Low Coherence</td>
<td>0,01</td>
<td>0,24</td>
</tr>
<tr>
<td>Very Low Coherence</td>
<td>0,25</td>
<td>0,44</td>
</tr>
<tr>
<td>Low Coherence</td>
<td>0,45</td>
<td>0,64</td>
</tr>
<tr>
<td>Something Is Coherent</td>
<td>0,65</td>
<td>0,99</td>
</tr>
</tbody>
</table>

Tab.2 Levels of coherence

Fig.15 It shows a screenshot from Matlab real-time DSP display. This EEG pair (F3-P4) was recorded with closed eyes condition. The first and the second plot (blue and red) show the time evolution of the two EEG channels (x axes show the number of samples that correspond to two seconds of signal). The stem plot (green) shows the coherence values in the alpha band frequency (about 7-14 Hz). The last plot (yellow) shows the two instantaneous values of power in alpha band of the two channels. Though the two signals may look different, this is due to changes in low frequency. In fact in alpha range their reach a good level of coherence.
2.2.2 EEG-based sound engine

Among the values of EEG coherence in input and the different sonification strategies, was applied a linear and directly proportional mapping to the input. The sound engine (fig.16), depending on the task, could receive input from two different sources. During certain phases of the pre-test the MIDI slider was used by the subject: with the purpose of explore the sonification, moving the slider he could control the sound output.

![Sound Engine Diagram](image)

Fig.16 Sound Engine structure.

During the experimental session, the trial generator randomly chooses one of three pairs of EEG signals. Each can be taken two times for a total of six trials. Then the sonification selector provides to activate the sonification request by the set of trials. There are three different available sonifications:

### Pitch Sonification

It is a patch (fig.17) that includes three oscillators corresponding to the fundamental and two harmonics. In fact as has been seen, changes in complex tones are more detectables than in pure ones. The sonification cover a musical extension of two octaves: from C2 to C4; for a total of 24 semitones. The changes between two successive inputs are smoothed, giving the impression of a continuous sound.

![Pitch Sonification](image)

Fig.17 Pitch Sonification
Rhythm Sonification

The rhythm sonification patch (fig.18) includes a 440 Hz oscillator driven by a reverse sawtooth generator. So the pulses vary in the range between 0 and 10 Hz while the pitch remains constant.

Fig.18 Rhythm Sonification

Hybrid Sonification

The hybrid sonification is the sum of the two prior sonifications (fig.19). Sound output produces both variations, changing at the same time in pitch and in rhythm. A low input produces a bass and continuous tone, while a high input produces a high pitched and very pulsed sound.

Fig.19 Hybrid Sonification
3 METHODS

3.1 Experiment design

This study introduces a new methodological approach to design EEG sonification experiments. A series of experimental sessions was developed to create an evaluation framework consisting of instantaneous EEG coherence, questionnaire responses and logs sent by the system during each respective session. The data was further processed to obtain a quantitative evaluation of the system that was designed.

3.1.1 Experimental setting definition

The experiment consisted of 4 parts:
- a pre-questionnaire;
- a preliminary test;
- a series of trials;
- a final questionnaire.

The objective of the task was to follow the sound variations through the use of a physical slider. During the pretest, the ranges of the sounds and of the slider were shown to the subject. The experiment consisted of three types of sonification, each containing six trials of 10-15 seconds. Between two trials there was a short pause. In summary the whole time required was about 40 minutes.

Sample - Sample consists in 12 subjects aged between 18 and 32 year (mean age of 25.16 y/old). None of the subjects had attended before any experiment similar to our proposed. Subjects were given an information sheet; informed consent was obtained by each subject. No control group was employed.

Questionnaire - In the pre-test questionnaire we asked about demographics, general music knowledge and presence of auditory lesions. The post-test questionnaire was based on a Likert scale of 5 point ranging from "not at all" to "very much". It proposed four different questions about general aspects of the task and two questions, one pair for each sound displayed, to rate pleasantness and difficulties of the three different sonifications.

Measures - We measure the subjective EEG coherence level in real time by means of a rating scaling from 0 to 127, based on a MIDI slider, using such device we were able to obtain a reliable and objective evaluation of sonification strategies.

Analysis - Correlation analysis between the objective levels of coherence and the subjective perceived ones by the sonification, for each sonification was conducted. Starting from the log file of each subject, the correlation coefficients was calculated at the 5% significance level, for each of the 6 trials and for each of the three sonification techniques, for a total of 216 r coefficients; p was always plenty smaller than 0.005. Mean, minimum and maximum were also calculated for each sonification technique.
3.1.2 Task design

In this study we compare the similarity between objective coherence (EEG recordings) and subjective coherence (subjects’ reports) perceived through auditory display. Each pair of EEG data was sonified and presented to the subjects. Using a MIDI slider (fig.20), subjects assess in real-time whether the signal instantaneous coherence can be perceived subjectively from the generated sound. Each subject performs the experiment listening 3 sequences of 6 trials: two repetitions in random order are present in each session (that was averaged). Also the sonification strategies were presented in a predetermined order different for each subject (tab.3).

<table>
<thead>
<tr>
<th>Sequences</th>
<th>1-2-3</th>
<th>2-3-1</th>
<th>3-1-2</th>
<th>3-2-1</th>
<th>2-1-3</th>
<th>1-3-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nº of subj.</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Tab.3 Order of presentation of the sonification strategies (1=Pitch, 2=Rhythm, 3=Hybrid).

Fig. 20 The Evolution UC-33e is an USB hardware controller designed to be used with any computer music/MIDI setup.

Log file structure

A log file is automatically filled during each experiment. It consists of 5 vectors that gather all the necessary information in order to conduct the statistical analysis (tab.4).

<table>
<thead>
<tr>
<th>Coherence</th>
<th>Midi Slider</th>
<th>Sonification Strategy</th>
<th>EEG Pair</th>
<th>Trial</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 127</td>
<td>0 to 127</td>
<td>1,2,3</td>
<td>1,2,3</td>
<td>1,2,3,4,5,6</td>
</tr>
</tbody>
</table>

Tab.4 shows the structure of the log file and the possible values that can be taken from each column.
3.1.3 Protocol

The experiments were conducted by the subjects sat in front of a MIDI controller. The subject could respond in real time to variations of the stimulus by moving the slider controller. Most of the choices in the experimental protocol were made to focus maximum attention of the subject. The protocol operated as following:

1. Subjects were given a short explanation of the experiment, then were asked to:
   - Fill a pre-questionnaire.
   - Wear headphones for the entire duration of the experiment;
   - Avoid to interact with objects different from the experimental environment;

2. A Pre-test stage, one for each different series of sound stimulus was presented to the subject. The pre-test consisted of two parts. In the first part the subjects listened to the whole range of sounds and were left free to explore the sound changes through the slider. In the second part was presented a predetermined set of stimuli and was asked to find them on the slider. The subject is invited to notice the differences between the minimum and maximum value of the scale.

3. The subject is asked to match the sonification variations which are listening by moving the MIDI slider.

4. The subject is asked to fill the final questionnaire.

In total the experiment consists in 3 pre-test stage and 3 series of 6 trials. Each experimental session (tab.5) took around 40 minutes.

<table>
<thead>
<tr>
<th>1)Pre-questionnaire</th>
<th>2)First Sonification pre-test</th>
<th>3)First Sonification test</th>
<th>4)Second Sonification pre-test</th>
<th>5)Second Sonification test</th>
<th>6)Third Sonification pre-test</th>
<th>7)Third Sonification test</th>
<th>8)Final Questionnaires</th>
</tr>
</thead>
</table>

Tab.5 shows the parts of which the experimental session consists.
4 EXPERIMENTAL RESULTS AND EVALUATIONS

4.1 Methods of analysis and evaluation

In Statistics correlation refers to a relationships involving dependence. A correlation coefficient is a number between -1 and 1 which measures the degree to which two variables are linearly related. If there is perfect linear relationship with positive slope, we have a correlation coefficient of 1; Positive values indicate that the two variables are positively correlated, meaning the two variables vary in the same direction. While with a negative correlation, whenever one variable has a high (low) value, the other has a low (high) value. A correlation coefficient of 0 means that there is no linear relationship between the variables.

Pearson's Product Moment Correlation Coefficient (PPMCC)

There are a number of different correlation coefficients that might be appropriate depending on the kinds of variables being studied. The most common of these, the Pearson correlation coefficient, is sensitive only to a linear relationship between two variables. Typically denoted by $r$, is a measure of the linear association between two variables (correlation), giving a value between +1 and −1 inclusive. It is widely used in the sciences as a measure of the strength (tab.6) of linear dependence between two variables.

<table>
<thead>
<tr>
<th>Correlation</th>
<th>Negative</th>
<th>Positive</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>−0.09 to 0.0</td>
<td>0.0 to 0.09</td>
</tr>
<tr>
<td>Small</td>
<td>−0.3 to −0.1</td>
<td>0.1 to 0.3</td>
</tr>
<tr>
<td>Medium</td>
<td>−0.5 to −0.3</td>
<td>0.3 to 0.5</td>
</tr>
<tr>
<td>Strong</td>
<td>−1.0 to −0.5</td>
<td>0.5 to 1.0</td>
</tr>
</tbody>
</table>

Tab.6 The interpretation of a correlation coefficient depends on the context and purposes. A correlation of 0.9 may be very low if one is verifying a physical law using high-quality instruments, but may be regarded as very high in the social sciences.
Computing correlation coefficients

To be a useful coefficient, this must be more than a number unique to a pair of variables. It must be a number comparable between pairs of variables. We must be able to compare correlations, so that we can determine whether trials change correlation with change in sonification. To process the 216 trials a Matlab code for the statistical analysis was written: initially, the log file of each subject was divided into three matrices each containing the data of a single sonification session, then each matrix was processed to extract the information of the six individual trials. Finally, on each trial was conducted an exploratory analysis, drawing the trends of the two variables (time plots and scatter plot) and calculating the respective correlation coefficient.

The function \([R, P] = \text{corrcoef}(x)\) was used to compute sample correlation and p-values.

Example:

\[
r22=\text{corrcoef}((\text{trial22(:,1)})',(\text{trial22(:,2)})');
\]

\[
R = \\
1.0000    0.9193 \\
0.9193    1.0000
\]

\[
P = \\
1.0000    3.007e-27 \\
3.007e-27    1.0000
\]

The outputs of \text{corrcoef} are 2 x 2 matrixes. The Pearson correlation coefficient appears twice as the (1,2) and (2,1) elements of the correlation matrix R, while the diagonal elements necessarily correspond to a correlation of a variable with itself, which necessarily is 1. Matrix P shows the correspondent p-values (which is very low).
4.1.1 Data exploration

4.1.1.1 Trials: Objective vs. Subjective reported Coherence variations

The objective values of coherence were rescaled from 0 to 1 to 0 to 127 and they are represented by the blue line. The values reported by the subject using the slider are shown in green. Two repetitions in random order are present in each session, for a total of 6 trials. Following as example, graphs concerning the subject 4 are shown:

Fig. 21 Sonified vs. Assessed coherence level during the pitch sonification session.

Fig. 22 The red line in the scatter plots is the reference; it represents the trend as if between the two variables there was a perfect overlap. (Correlation coefficient= 1).
Rhythm sonification session

Sonified vs. Assessed

![Trial scatter plots](image)

Fig. 23 Sonified vs. Assessed coherence level during the rhythm sonification session.

Trial scatter plots

![Trial scatter plots](image)

Fig. 24 Scatter plots between objective coherence and subjectively assessed by the MIDI slider. The red line in the scatter plots is the reference; it represents the trend as if between the two variables there was a perfect overlap. (Correlation coefficient= 1).
Hybrid sonification session

Sonified vs. Assessed

Fig. 25 Sonified vs. Assessed coherence level during the hybrid sonification session.

Trial scatter plots

Fig. 26 Scatter plots between objective coherence and subjectively assessed by the MIDI slider during the hybrid sonification session. The red line in the scatter plots is the reference.

The complete list of graphs for all subjects is present in Appendix B.
4.1.2 Correlation Analysis

4.1.2.1 Trial Correlation Coefficients

Starting from the log file of each subject, the correlation coefficients was calculated at the 5% significance level, for each of the 6 trials and for each of the three sonification techniques, for a total of 216 r coefficients; p was always plenty smaller than 0.005. Each of the following tables contains the values obtained during the trials by each subject. Mean, minimum and maximum were also calculated for each sonification technique.

<table>
<thead>
<tr>
<th>Subject 01</th>
<th>Trial 1</th>
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<th>Trial 3</th>
<th>Trial 4</th>
<th>Trial 5</th>
<th>Trial 6</th>
<th>MEAN</th>
<th>MIN</th>
<th>MAX</th>
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</thead>
<tbody>
<tr>
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<td>-0.0179</td>
<td>-0.3311</td>
<td>0.6190</td>
<td>0.9027</td>
<td>0.5189</td>
<td>0.8313</td>
<td>0.4205</td>
<td>-0.3311</td>
<td>0.9027</td>
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<tr>
<td>Rhythm</td>
<td>0.6614</td>
<td>0.6599</td>
<td>0.8689</td>
<td>0.5840</td>
<td>0.1706</td>
<td>0.1569</td>
<td>0.5170</td>
<td>0.1569</td>
<td>0.8689</td>
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<td>0.6680</td>
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<td>0.7377</td>
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<th>MEAN</th>
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<th>MAX</th>
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### 4.1.2.2 Coefficient distribution

Aggregate data

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<td>12</td>
<td>0.6172</td>
<td>0.7122</td>
<td>0.9107</td>
</tr>
<tr>
<td>TOTAL</td>
<td>0.4456</td>
<td>0.6961</td>
<td>0.8737</td>
</tr>
</tbody>
</table>

Tab. 7 The table shows the 6 trials average values of the mean, of the minimum and maximum for each sonification technique. The last line shows the average values.
Trial distribution

Fig. 27 The histogram represents the distribution of the 72 correlation coefficients. It is clearly visible that a large number of trials reaching high levels of correlation.

Fig. 28 The box plot shows how the trials are distributed within each sonification. In particular, the hybrid sonification has higher mean and smaller variance than the other two strategies.

Test of normality

The Matlab function “kstest(x)” performs a Kolmogorov-Smirnov test to compare the values in the data vector x to a standard normal distribution. The null hypothesis is that x has a standard normal distribution. The alternative hypothesis is that x does not have that distribution. The result H is 1 if the test rejects the null hypothesis at the 5% significance level, 0 otherwise.

Pitch trial distribution: \( H = 1 \) with \( p = 6.5269 \times 10^{-23} \) The null hypothesis was rejected.
Rhythm trial distribution: \( H = 1 \) with \( p = 3.4650 \times 10^{-18} \) The null hypothesis was rejected.
Hybrid trial distribution: \( H = 1 \) with \( p = 3.0071 \times 10^{-27} \) The null hypothesis was rejected.
4.1.3 Sonification strategies evaluation

Fig. 29 shows the mean performances based on the average of the trials of each subject for each sonification. Sonification scores = P 0.6961  R 0.6059  H 0.7441

Fig. 30 shows the mean of the worse performances of each subject for each sonification. Sonification minimum scores = P 0.4456  R 0.3104  H 0.5446
Fig. 31 shows the mean of the best performances of each subject for each sonification.
Sonification maximum scores =  P 0.8737   R 0.8490  H 0.8995

ANOVA

This test makes the assumption of data normality. Normality tests reveal that features treated for analysis do not come from normal population. These results are therefore to be taken with caution. Below are displayed only the analysis in which the means between groups resulted significantly different.

Pitch vs. Rhythm

Fig. 32a-b ANOVA performed between the coefficients distributions of pitch and rhythm sonification.

<table>
<thead>
<tr>
<th>Source</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>Prob&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Columns</td>
<td>0.29209</td>
<td>1</td>
<td>0.29209</td>
<td>5.36</td>
<td>0.022</td>
</tr>
<tr>
<td>Error</td>
<td>7.73882</td>
<td>142</td>
<td>0.0545</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>8.03101</td>
<td>143</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Rhythm vs. Hybrid

Fig.33a-b ANOVA performed between the coefficients distributions of rhythm and hybrid sonification.

<table>
<thead>
<tr>
<th>Source</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>Prob&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Columns</td>
<td>0.68723</td>
<td>1</td>
<td>0.68723</td>
<td>16.82</td>
<td>5.88312e-005</td>
</tr>
<tr>
<td>Error</td>
<td>5.80105</td>
<td>142</td>
<td>0.04085</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>6.48828</td>
<td>143</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Rhythm vs. Pitch and Hybrid Sonification

Fig.34a-b ANOVA performed between the coefficients of rhythm and the other two sonifications.

<table>
<thead>
<tr>
<th>Source</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>Prob&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Columns</td>
<td>0.7084</td>
<td>2</td>
<td>0.35419</td>
<td>7.91</td>
<td>0.0005</td>
</tr>
<tr>
<td>Error</td>
<td>9.5362</td>
<td>213</td>
<td>0.04477</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>10.2446</td>
<td>215</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.1.4 Inspection of subjective reports

4.1.4.1 Subject background

Q.: Do you have any musical experience or background?

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Very much</td>
</tr>
</tbody>
</table>

Not at all

1 - Not at all 3 25%
2 - 4 33%
3 - 2 17%
4 - 2 17%
5 - Very much 1 8%
Mean: 2.78

4.1.4.2 Task evaluation

Q.: Did you find the tasks challenging?

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Very much</td>
</tr>
</tbody>
</table>

Not at all

1 - Not at all 0 0%
2 - 0 0%
3 - 2 17%
4 - 8 67%
5 - Very much 2 17%
Mean: 4.00

Q.: Was it difficult to be concentrated on the task?

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Very much</td>
</tr>
</tbody>
</table>

Not at all

1 - Not at all 1 8%
2 - 4 33%
3 - 4 33%
4 - 3 25%
5 - Very much 0 0%
Mean: 2.75
Q.: Was it difficult to follow the sounds with the slider?

<table>
<thead>
<tr>
<th>Rating</th>
<th>Count</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - Not at all</td>
<td>1</td>
<td>8%</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>17%</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>42%</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>25%</td>
</tr>
<tr>
<td>5 - Very much</td>
<td>1</td>
<td>8%</td>
</tr>
</tbody>
</table>

Mean: 3.08

Q.: Did you feel tired after finish the tasks?

<table>
<thead>
<tr>
<th>Rating</th>
<th>Count</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - Not at all</td>
<td>1</td>
<td>8%</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>33%</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>17%</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>33%</td>
</tr>
<tr>
<td>5 - Very much</td>
<td>1</td>
<td>8%</td>
</tr>
</tbody>
</table>

Mean: 3.00
4.1.4.3 Sound perception: sonification pleasantness

Q.: How pleasant was the pitch-based sound?

<table>
<thead>
<tr>
<th>Rating</th>
<th>Frequency</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - Not at all</td>
<td>1</td>
<td>8%</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>17%</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>42%</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>33%</td>
</tr>
<tr>
<td>5 - Very much</td>
<td>0</td>
<td>0%</td>
</tr>
</tbody>
</table>

Mean: 3.00

Q.: How pleasant was the rhythm-based sound?

<table>
<thead>
<tr>
<th>Rating</th>
<th>Frequency</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - Not at all</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>83%</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>5 - Very much</td>
<td>2</td>
<td>17%</td>
</tr>
</tbody>
</table>

Mean: 3.33

Q.: How pleasant was the hybrid-based sound?

<table>
<thead>
<tr>
<th>Rating</th>
<th>Frequency</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - Not at all</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>33%</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>50%</td>
</tr>
<tr>
<td>5 - Very much</td>
<td>2</td>
<td>17%</td>
</tr>
</tbody>
</table>

Mean: 3.83
4.1.4.4 Sound perception: difficulty

Q.: Was it difficult to perceive the variations with the pitch-based sound?

Not at all | Very much
--- | ---
1 | 2
3 | 4
5

<table>
<thead>
<tr>
<th>Level</th>
<th>Not at all</th>
<th>Very much</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>5</td>
<td>42%</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>4</td>
<td>25%</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>Mean: 2.92</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Q.: Was it difficult to perceive the variations with the rhythm-based sound?

Not at all | Very much
--- | ---
1 | 2
3 | 4
5

<table>
<thead>
<tr>
<th>Level</th>
<th>Not at all</th>
<th>Very much</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>7</td>
<td>58%</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>4</td>
<td>33%</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>Mean: 2.75</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Q.: Was it difficult to perceive the variations with the hybrid sound?

Not at all | Very much
--- | ---
1 | 2
3 | 4
5

<table>
<thead>
<tr>
<th>Level</th>
<th>Not at all</th>
<th>Very much</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>6</td>
<td>50%</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>Mean: 2.33</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.1.4.5 Sound perception: sonification evaluation

Q.: Do you prefer the pitch based, the rhythms based or the hybrid sonification?

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch</td>
<td>2</td>
<td>17%</td>
</tr>
<tr>
<td>Rhythm</td>
<td>4</td>
<td>33%</td>
</tr>
<tr>
<td>Hybrid</td>
<td>6</td>
<td>50%</td>
</tr>
</tbody>
</table>
5 DISCUSSIONS AND CONCLUSION

5.1 Discussions

5.1.1 Validity of the results

There is a clear correlation between subjective perception of sound and objective EEG coherence. The analysis for the evaluation of different sonification strategies has clearly shown that the hybrid solution has obtained higher correlation values respect to the other sonification strategies proposed. This allowed subjects to perceive in a more accurate and precise way objective changes of coherence. The hybrid sonification has achieved an average correlation of $r=0.7441$ and a maximum average value of $r=0.8995$. The other sonifications have achieved lower results, though still above a value of correlation $r$ of 0.6 (and maximum $r$ higher than 0.8); $p$ was always plenty smaller than 0.005. The sonification based on rhythm variations reached the worse performance; furthermore ANOVA analysis revealed that this result is significantly different from those obtained from the other two (pitch and hybrid) sonifications.

The lower values obtained in some trials (including cases of non-correlation) are due to imperfections in the protocol and in training errors, rather than real problems of perception. We must consider that all subjects who underwent the experiment had never participated in a similar type of task. Surely improving the pre-testing and learning stage, it could further improve the good results achieved.

Since the variations of perceived coherence mostly oscillate near of the objective values of coherence, the result achieved is very good. In fact, if the values are rescaled from 0-127 to 0-1, i.e. an error of 10 points made with the slider corresponds to an error of 0.078 in terms of estimated coherence, which is a relative low value. Instead, the most pronounced discrepancies could have other causes. The comparison between the graphs of objective coherence and the values of perceived coherence shows that subjects tend to overestimate the changes in the sound. What really is perceived is the relative change between two successive values, not the new value in absolute terms. A marked difference between two successive values produces a marked change in the control of the slider. That is, a change in the stimulus from a medium stimulus to a loud (bass) stimulus produces a perception of a stimulus subjectively higher (lower). This problem could be solved in future applying a Proportional-Integral-Derivative (PID) Control that could be implemented to drive the sound engine.

The questionnaires confirmed the results obtained from the objective analysis. The hybrid sonification appears to be favoured by the subjects, achieving half of the vote. In addition, the hybrid sonification was found to be the most pleasant and less difficult to perceive the changes. The questionnaires also revealed that the tasks have proven to be quite challenging and their duration a little tiring. This may have influenced the performance in the last set of trials. Future experiments could be revised to take less time.
5.1.2 Problems faced by the study

Design issues

The initial stage of this work has been entirely devoted to design a suitable experimental setting. The first set of preliminary attempts allowed to detect errors and to identify elements to be improved. As a first approach was thought to apply a direct sonification of two EEG channels power bands to assess subjective coherence; but this would been as difficult as detecting coherence in a graphic plot of the temporal structure of the two channels, even though, our expectation was that it would been easier to detect such features through sound. In fact the sonification of the two power bands means not providing an explicit value of the coherence quantity. Also the FM sonification approach shared the same limitation, both sonification strategies received as input two flows of values, the alpha power band variation for each channel: FM sonification drove a single sound but this did not respond to any correlation factor of EEG channels, it changed only the mapping but not the kind of input.

The idea of using a change of domain (from visual to auditory) not only to show information but also to boost human capacity is very attractive, but it is something still not explored and surely it is a study that requires years. On the other hand, the level of coherence is the property that the two EEG signals share. Making explicit this measure, it was possible to decrease the number of variables to sonify from two (power bands) to only one (coherence). Implementing the compute of coherence in real time also permitted to directly compare an objective EEG feature (coherence) with a vector of subjective values obtained by the MIDI slider.

Reversibility vs. Intuitivity

Considering the reversibility of a sonification, the property of being able to return to the original signal or features from a given EEG data. It possible to define a trade-off between intuitivity and reversibility. Early trials showed that more a sonification is reversible, less intuitive it is. This because a reversible sonification handles many parameters of the signal; having a high number of degrees of freedom, is an arduous task finding a way to produce a sound that is not difficult to understand.

Arbitrary sound mapping

Currently each research group presents its own sound mapping, often based on arbitrary choices. In general all sound parameters are under the control of the human “sonifier”. This allows the exploration of multiple parameter mappings, as the independent control of pitch, duration, volume, etc. There would need to base sonification less on arbitrary choices, and more on studies of auditory perception.
5.1.3 Future steps

In this work, in order to evaluate the performance of the system dealing with basic audio stimuli, it was decided to concentrate on sonification mappings based on simple sound. Next steps will take into consideration to test and evaluate more complex sonification strategies, such as FM sonification driven by EEG coherence. Another need could be to explore different kinds on mapping that could improve the sonification perception. The reduction of the bias will be a primary goal of future work, a study involving the exploration of other devices for real-time sonification perception assessment as well as implementation and evaluation of non-linear mappings, would be desirable. From a viewpoint of control systems, a solution could be reached implementing a Proportional-Integral-Derivative (PID) Control to drive the sound engine. In fact a PID controller calculates an "error" value as the difference between a measured process variable and a desired setpoint. The controller attempts to minimize the error by adjusting the process control inputs. In particular derivative control is used to reduce the magnitude of the overshoot, which is seen to be the main cause of bias in the assessment of sonification perception.

The Matlab code for sonification evaluation could be upgrade to receive data logs in real-time. In this way became possible to develop a sonification that is able to auto-calibrate and auto-evaluate itself making also real-time adjustment in the mapping and in the sound. Outlier detection and deletion could be also implemented to improve the code of sonification evaluation.

Finally in the future we planned to move from off-line to real-time EEG sonification to test it in collaborative performance (i.e. Music collaboration). Furthermore we are also interested to investigate the biofeedback effect of the EEG coherence sonification on divergent thinking collaborative and creative tasks [49].
5.2 Conclusions

The main goal of the work in this thesis has been to find a sonification strategy that ensures that the EEG features be perceived as accurately as possible. In this project we have presented three different sonification strategies and we compared match between objective and subjective coherence according to the sonification mapping we tested. The correlation analysis has shown that the Hybrid sonification achieved the better results.

This study introduces a new methodological approach to design EEG sonification experiments that confirms the hypothesis about the evidence of auditory display techniques. Moreover, it provides a framework for a reliable and objective evaluation of sonification strategies. There are many works in the literature using sonification based on variations in pitch, rhythm or even of much more complex structures. Instead there are scarce studies on the sonification of EEG coherence. What does not exist is a method to assess objectively their functioning. And this is what has been also attempted in this study.

We believe that this study is only a first exploration in the path for a most robust sonification system and evaluation framework. The good and encouraging results achieved are encouraging to pursue a project full of suggestions and opportunities for future evolutions.
REFERENCES

[27] www.sensorband.com/atau/
[29] www.oboro.net/archive/exhib0001/neam/neam.html


Starlab Enobio. Wireless BCI device (www.starlab.es)

http://processing.org/

http://www.mathworks.com


http://puredata.info/

http://cycling74.com/

http://opensoundcontrol.org/


APPENDIX A

Matlab code

1. DSP

1.a Alpha Power Bands calculation

%1st Channel

[power,f] = eegFFT(wineeg, Fs); %(fft function from: http://www.mathworks.com/support/tech-notes/1700/1702.html)

powerEEG = power;
power_alpha = ((powerEEG(7)+powerEEG(8)+powerEEG(9)+powerEEG(10)+powerEEG(11)+powerEEG(12)+powerEEG(13)+powerEEG(14));

%in that case freq. bins correspond to real freq.

%2nd Channel

[power2,f] = eegFFT(wineeg2, Fs);
powerEEG2 = power2;
power_alpha2 = ((powerEEG2(7)+powerEEG2(8)+powerEEG2(9)+powerEEG2(10)+powerEEG2(11)+powerEEG2(12)+powerEEG2(13)+power2(14));

%Send to PD

pack_array = horzcat(power_alpha, power_alpha);
fwrite(udpport, int16(pack_array));

1.b Coherence

%Receiving EEG recordings..
Data = eegtrack();
sigx=double(Data(1,:));
sigy=double(Data(2,:));

%Cohherence calculation
[Cxy,F] = mscohere(sigx,sigy,[],[],[],500);

%Selecting only alpha band frequencies
Cohsum=Cxy(8:15);

Send to PD

coherece = (sum(Cohsum)/length(Cohsum))*255; %averaging and rescaling from 0-1 to 0-255 in order to use all the range of the UDP protocol.
fwrite(udpport, coherence);
APPENDIX B

Subject 01

PITCH

RHYTHM

HYBRID
Subject 04

PITCH

RHYTHM

HYBRID
Subject 06

PITCH

RHYTHM

HYBRID
Subject 07

**PITCH**

![Pitch Graphs]

**RHYTHM**

![Rhythm Graphs]

**HYBRID**

![Hybrid Graphs]
Subject 08

PITCH

RHYTHM

HYBRID
Subject 09

PITCH

RHYTHM

HYBRID
Subject 10

PITCH

RHYTHM

HYBRID
Subject 11

PITCH

RHYTHM

HYBRID
Subject 12

PITCH

Trial 1

 Trial 2

 Trial 3

 Trial 4

 Trial 5

 Trial 6

RHYTHM

Trial 1

 Trial 2

 Trial 3

 Trial 4

 Trial 5

 Trial 6

HYBRID

Trial 1

 Trial 2

 Trial 3

 Trial 4

 Trial 5

 Trial 6