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***Abstract*—While an extensive palette of sound and visual generation techniques have been developed during the era of digital signal processing, the design of innovative virtual instruments has come to dramatic fruition over the last decade. The use of measured biological signals to drive these instruments proposes some new and powerful tools for clinical, scientific and artistic applications. Over the period of one month - during the eNTERFACE'07 summer workshop in Istanbul, Turkey - researchers from the fields of human-computer interfaces, sound synthesis and new media art worked together towards this common goal. A framework for auditory display and bio-musical applications was established upon which were based different experimental prototypes. Diverse methods for the analysis of measured physiological signals and of mapping the extracted parameters to sound and visual synthesis processes were explored. Biologically-driven musical instruments and data displays for clinical and medical purposes were built. From this have emerged some worthwhile perspectives on future research. This report summarises the results of that project.**

***Index Terms*—Multimodal interfaces, biosignals, brain-computer interfaces, sonification, auditory display, interactive arts, biologically-augmented performances.**

I. Introduction

There is already a rich history of people using measured biological signals to generate visual and auditory displays. Scientists, physicians and artists have been using these techniques to understand, analyse and gain insight into ongoing biological processes for almost 200 years. René-Théophile-Hyacinthe Laennec invented the stethoscope and the technique of mediate auscultation to listen to and diagnose maladies of the lungs and heart nearly 200 years ago [1].

Since that time, the techniques of visual and auditory display of biological signals have been important tools used in the interpretation and diagnoses of human biological processes as indicators of sickness and of health. The extent to which these tools have penetrated the day-to-day practices of scientists, clinicians and physicians is not really questioned. There is currently, however, a predilection for the use of visual techniques for such displays which is - given the overtly visual bias of our modern culture - not surprising. At the same time it is worth noting that one of the first techniques which aspiring young physicians learn to do is listening - mediate auscultation - to the heart, to the lungs, to the internal body processes. By the time these people become doctors they already have a finely tuned sense for the sounds of sickness and of health.

Many biological signals are indeed fascinating and challenging objects of study, but, somehow, those of the human brain prove to be the most promising yet problematic. The use of sonification to help understand brain activity goes back to the first confirmation of Hans Berger's tentative explorations into the human Electroencephalogram [2]. From the mid-1960s until the late 1970s a series of composers and artists including Alvin Lucier and David Rosenboom began experimenting with the use of brainwaves and other biological signals to drive sound and visual events [3][4]. Then, in the early 1990s, Benjamin Knapp and Hugh Lusted began working on a human-computer interface called the *BioMuse* [5][6]. This permitted a human subject to control certain computer functions via bioelectric signals. In 1992, Atau Tanaka [7] 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, during live performances throughout the 1990s. In the current project, we wish to continue the path initiated by these early pioneers and which we have explored during the two previous eNTERFACE workshops [8][9] by investigating how ongoing measured biological signals can be used to provide insight and clarity to the -scientific and artistic - ways of understanding our own biological realities. An exhaustive review of the state

This report, as well as the source code for the software developed during the project, is available online from the eNTERFACE'07 web site: www.enterface.net.

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of the art in both biosignal sonification and physiologically-driven musical interfaces is provided in [8] and [9].

In this current project, we intend to continue this established field of research and hopefully add some useful and innovative perspectives to the ongoing practice [10]. Practically, the present work was conducted within the framework of the third eNTERFACE workshop, which took place in Istanbul, Turkey between July 16th and August 10th 2007. During four weeks, a multidisciplinary team, composed of experts from the fields of human-computer interaction, neurophysiology, and sound and music computing have worked together on the development of a robust and reusable framework for the capture and the processing of physiological signals geared towards sound and visual creation applications. With a total of 16 members from labs all over the world, our team had a very broad skill and interest range, from more technical aspects of signal acquisition, to musical performance. The team was divided into a number of smaller interest groups to tackle different aspects of the project. A large set of biosignals was considered and two main approaches were followed, implying different strategies for the design of the sonic interactions. In the first one, we attempted to develop applications aiming at exploiting sound to help the monitoring of the physiological state of a subject in a closed feedback loop, whereas in the second approach, relying on more aesthetic considerations, the objective was to create interactive art performances that fully depend on the physiological state of the performer.

This report presents the main outcomes of this project; it is composed of two main sections resulting of these two approaches: the first section presents the sonification-oriented part of our project aiming at developing a EEG-guided control system giving a visual and sonic feedback of a human brain activity. The second section of the report describes our artistic-oriented approach of the biologically-controlled interfaces, by detailing the *Bio-Music* platform we set up as the result of the workshop and the three artistic performances that were premiered at the end of the project.

II. Audio-visual feedback of brain activity

A. Introduction

Sonification is the use of non-speech audio to convey information [11]. *Interactive Sonification* (IxS) a more recent specialisation, takes advantage of the increasing availability of sensing and actuating technologies [12]. In IxS, the listener is actively involved in a perception/action loop, and the main objective is to generate sonic feedback which is coherent with interactions performed upon sonically-augmented artefacts. This allows active explorations of information via more engaging and meaningful modalities. A promising IxS approach is *Model-based Sonification* [13], in which the sound emerges as an organic product of interactions between a model and an external agent.

The sonification of EEG data for monitoring and offline analysis has been already investigated from a research point of view (see e.g. [14],[15] and the references therein). These implementations generally use either *audification* [14], or a kind of *parameter mapping*, i.e., controlling the synthesis parameters via arbitrary transformations of features derived from the data [11].

IxS has begun to exploit the fact that people can self-regulate their brain activity based upon auditory feedback [16]. This notion is essentially the same as 'Biofeedback' - an idea which came to some prominence in the 1970s. The resulting device - parametric orchestral sonification of EEG in real-time (POSER) - allows auditory feedback of multiple EEG characteristics using the MIDI protocol. Six frequency bands of increasing centre frequency (slow cortical potentials (SCP), delta, theta, alpha, beta, and gamma) are assigned as instruments on a MIDI device. Two different classes of instruments are used: pitched percussive instruments (delta, theta, alpha) and smooth continuous instruments such as synthesiser, pads and ocarina (SCP, beta, gamma).

The POSER relies on parameter mapping sonification: the timing, pitch, and volume of the instruments are modulated by the features extracted from the frequency bands. The guidelines for sound design in auditory feedback are based upon a previous study [17], which compares the auditory, visual, and audiovisual feedback modes and concludes that audiovisual feedback mode shows no statistically-significant performance increase over simple audio or visual feedback.

In a pilot study with the POSER system, the subjects received full orchestral feedback of their brain activity from one channel of EEG. Initially, they were introduced to each instrument, they were then visually instructed to focus their attention upon either the rhythmic, percussive instruments or upon the continuous instruments for 8 seconds. After a 2-seconds resting interval, the next trial begin. 200 trials for 10 participants were collected. The results indicate that the participants exhibit impressive abilities for auto-regulation: five participants could regulate the amplitude of multiple frequency bands, four participants exhibited significant amplitude changes in the alpha band, and power spectra in beta and gamma wavelengths revealed significant differences in most of the subjects [16].

During this workshop, we set out to develop an EEG-guided control system in line with traditional brain-computer interface (BCI) technology ([18]). The latter uses the potentials emitted by certain pyramidal cell population of the grey matter of the brain to control computers (BCI) or machines (BMI). The development of such interface technology is hitherto mainly motivated as a rehabilitation and communication aid for paralysed patients and other motor-deficient patients. However, recent advances in the fields of EEG measurement and analysis tools along with increased computational processing power suggest possible uses of such techniques for non-medical applications. In this aspect our goal was twofold:

- Firstly, we wanted to build a system which enabled the user to control or manipulate auditory output using motor imagery and action. In order to have as much freedom as possible in the control of auditory output, we pursued the possibility of being able to discriminate between multiple, different tasks. This study was made offline and is described in section II-B.
- Secondly, we aimed at developing a neuro-feedback system which reflects certain aspects of the users cerebral ac-

tivity using visual and/or auditory means, and thus gives the user the opportunity to experience and manipulate these features of her brain activity more consciously. This study was made online and is described in section II-C.

Multi-category classification of motor tasks gave results slightly better than pure chance, however, online control of a ball in 2-dimensions gave interesting results and proved that visual and auditory feedback can improve the user's discriminatory control.

B. *Offline analysis*

1) Materials: The system used for EEG acquisition was a Leonardo EEG/PSG system with up to 32 EEG channels and 6 PSG channels. A custom Matlab program acquired the data from an RS232 port. The cap is a low-cost swimming cap made of elastic nylon in which holes have been made according the 10/20 electrode placement system. Individual electrodes are then placed - via the given holes - on the scalp with conductive paste. For online real-time purposes, the acquisition algorithm was written in C and compiled in the Matlab environment.

Pre-processing: No muscular artefact removal algorithms were used, but the subject was asked to avoid eye blinking and extraneous movement as much as possible.

2) Experiment paradigm: The aim of this experiment was to discriminate between EEG patterns related to different motor tasks which would then be used to drive sound and visual synthesis processes. A visual stimulus was presented to the subject, displaying a word corresponding to a task which the subject is trying to achieve (i.e move left finger, right finger, left foot, right foot, tongue, relax). A reference cross was fixed in the centre of the display in order to give a point of reference to the subject and to limit EOG artefacts.

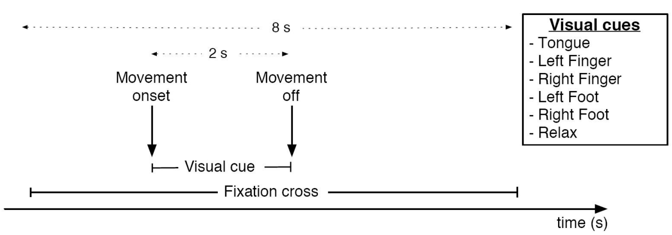

Fig. 1. EEG experiment paradigm. To avoid eye movements, a reference cross is displayed. Every six seconds, one of six motor tasks appear on the screen for two seconds.

3) Event Related Potentials analysis: In order to investigate the potentials related to the different tasks which were actuated, we extracted either time or frequency features to train a classifier.

a) Event-related potential (ERP) analysis using time features: The trials were high-pass filtered with a cutoff frequency of 2 Hz. For each trial we applied a baseline correction with the mean value of the interval from 400 to 50 ms before stimulus onset. We applied a bootstrap significance test to investigate the differences between the conditions [19]. To remove excessive artefacts like eye-movements, we employed a threshold criteria of +/- 50 microV.

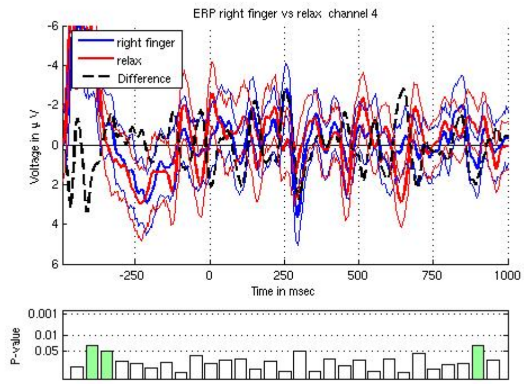

Fig. 2. The difference wave (black) for the right finger (blue) vs relaxed (red) condition at the left central electrode (C3). Standard deviation of mean is indicated by the thinner red and blue lines surrounding the respective signals.

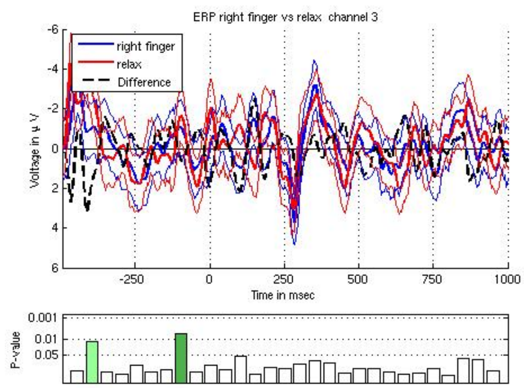

Fig. 3. The difference wave (black) for the right finger (blue) vs. relaxed (red) condition at the right central electrode (C4). Standard deviation of mean is indicated by the thinner red and blue lines surrounding the respective signals.

For the trial averages for channels F3, F4, C3, C4, P3, P4, O1, and O2 no significant differences between the control condition (relaxed) and each of the five other conditions (left finger, right finger, left foot, right foot, tongue) were found (see Fig.2 and 3 for examples).

b) Event-related potential (ERP) analysis using frequency features: Short Term Fourier Transform (STFT): STFT coefficients were computed over the 2 seconds following the stimulus onset. Each STFT coefficient is considered as a feature in our feature vector. A STFT with window length of 64 points and FFT length of 64 points was used for feature extraction. The STFT features from 8 channels were combined to shape the feature vector of each trial.

c) Classification and results: In order to select the most relevant features, the fischer reduction technique was used. The high dimension feature vector for each trial was thus reduced to a two-dimensional vector (Fig.4). Three classifiers were trained on the reduced feature vector, Polynomial Support Vector Machines (P-SVM), Linear Support Vector Machines (L-SVM) and Linear Discriminant Analysis (LDA).

Differentiating all 6 tasks led to results only slightly better than chance, we therefore grouped all four limb movements

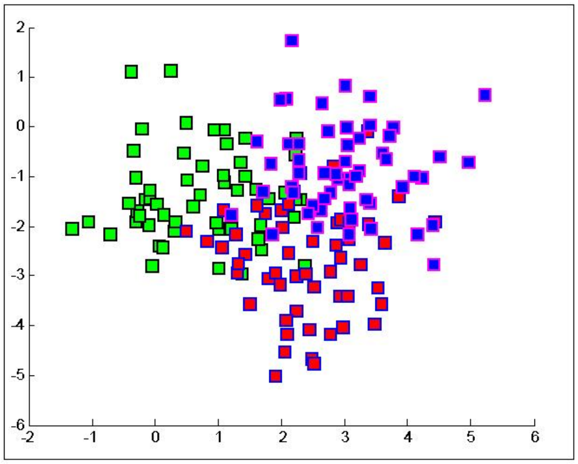

Fig. 4. Example of a 2-D feature vector for a training set. Each square shows a trial which is projected on two dimensional space by fisher projection. Three different classes are shown: state of rest (green), tongue movement (blue) and limb movement (red).

into one category and decided to classify only three conditions : relaxed rest condition, tongue movement and limb movements. The results are shown in table I. These outcomes are disappointing probably because of muscle artefacts stemming from the actual movements.

TABLE I

CLASSIFICATION RESULTS FOR THREE TASKS: REST (R), TONGUE (T) AND LIMB MOVEMENTS (M). THE RESULTS ARE SHOWN WITH AND WITHOUT BAND PASS (BP) FILTERING. THREE CLASSIFICATION METHODS ARE USED, POLYNOMIAL SUPPORT VECTOR MACHINES (P-SVM), LINEAR SUPPORT VECTOR MACHINES (L-SVM) AND LINEAR DISCRIMINANT ANALYSIS (LDA)

	3 class (T,M and R) no BP	3 class (T,M and R) with BP
P-SVM	41.5%	43.1%
L-SVM	42.92%	45.45%
LDA	41.6%	43.7%

4) Discussion: To simplify the task for the experimental subject, we used real movement instead of imagined movement. This approach might be especially interesting for the implementation of BCI systems for real-world interactions and performance, which is usually accompanied by external artefacts (e.g. muscle activity, ocular artefacts). Therefore, a BCI system which can function in situations where the user is moving would be a big advantage over the typical systems which work well only in an artificial, almost noise-free context. However, we encountered many obstacles in our approach and there remain some key issues germane to the further development of an EEG-guided motion-resistant control system. The analysis of the data showed no significant differences between event-related potentials of the different conditions. The data suffered from variance introduced by motion artefacts, latency and jitter. To reduce the variance one should use electrodes (EMG) to detect the movements and then to average the signals aligned by the onset of movement to obtain the motor readiness potential [20]. Furthermore, the application of sophisticated artefact reduction techniques (e.g. ICA or regression-based methods for muscle and eye-movement artefact removal) might delay the recognition of mental tasks absolved but could increase the effective signal-to-noise ratio and thus the probability of correct recognition.

Further, a smaller variance between trials of one condition in motor imaginary approaches might be achieved by subject training. Here, sonification and visualisation techniques can give the subject a clearer understanding of her brain dynamics relative to the signal to produce. This is what we studied in the MiniBall experiment which is described in the following section.

C. Online Analysis

As stated in [18] *"BCI use is a skill"*. To master this skill, the user needs to train on a mental task. The use of feedback helps considerably and yields more accurate results.

Different types of feedback have been studied, for example, visual, haptic [21], vibrotactile [22] and auditory feedback [23]. Auditory feedback has been seldomly used but could prove very useful for blind disabled. A recent study [24] uses sounds coming from two different instruments as a feedback for the user. Although the learning time is longer for the auditory feedback, in the end results are similar with visual or auditory feedback.

The aim of this study was to compare visual and auditory feedback for a 2D cursor movement. Experiments were made on an untrained subject. The goal was to control a ball on the screen and drive it to a rectangular box in the top-right of the screen (Fig.5). Horizontal and Vertical movements were controlled by the spectral power in alpha and beta bands. The subject was not restrained by a particular protocol within the feedback, rather he was encouraged to find the states most effective for alpha and beta manipulation himself. This resulted in the vivid imagination of the subject flying through complex cloud formations. Indeed, this task not only induces alpha waves, because of the feeling of relaxation drawn from the sensation of flying, but also beta waves since the user achieves high cognitive visualisation tasks.

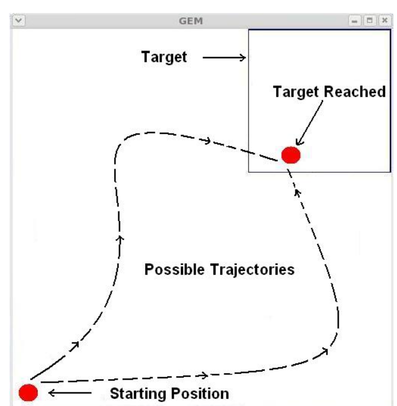

Fig. 5. Screen capture of the MiniBall interface. Horizontal and vertical movements of the ball are controlled via the spectral power in alpha and beta bands. The user is free to adopt any trajectory as long as the ball reaches the target.

Results were measured in seconds, i.e the time needed for the user to reach the target. Either visual or auditory feedback gave similar results, less than five seconds. These results are significantly better than without feedback. However the combination of visual and auditory feedback led to poorer results, perhaps because of an inconvenient work overload.

The operating system and the audiovisual synthesis is presented in the next few paragraphs.

1) Operating system: Data acquired by the system described in II-B1 is sent via UDP to Simulink (fig. 6). Only one electrode (F3) was used for the following experiment. The sampling rate was 200Hz, and data from F3 was bandpassed filtered using a Simulink block provided by an open source software, rtsBCI available on the Biosig web pages[1]. Alpha and beta bands were chosen between [8-12]Hz and [13-20]Hz respectively. A FIR filter of order 5 was used. Samples of spectral powers of alpha and beta bands are then sent with the OSC protocol with a hand-made level-2 m-file S-function.

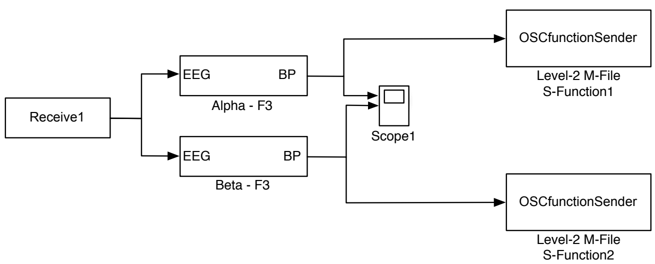

Fig. 6. Block diagram of the Simulink model. Data is received via UDP, band powers of alpha and beta bands are computed, then sent through OSC to the audiovisual synthesis.

Simulink was chosen for it's flexibility and rapid prototyping capabilities. In further work we will consider using more electrodes and more complex signal analysis.

2) Description of the audiovisual synthesis: We had an audiovisual operant conditioning training system in mind, and chose the pd-GEM environment as the implementation platform. The block-diagram in Fig. 7 illustrates the structure of our system $MiniBall\_EEG$. $MiniBall\_EEG$ receives OSC streams or reads pre-recorded measurement data. The OSC streams follow our namespace convention. Currently, energy in the alpha and beta bands of a fixed channel is received. In the Source Selection block, other channels can be listened to by manual routing. Very primitive probing of the incoming data levels - akin to the parallel time-series visualisation - is provided. The probed signal levels inform the scaling values in the next block Preprocessing. The alpha-band energy is first hard-limited within the range [α_{min} , α_{max}] then linearly mapped to the normalised range $\bar{\alpha} \in [-1, 1]$. The beta-band is processed similarly. In both bands, good results are obtained with the values 0.01 and 512 as minimum and maximum values, respectively. These normalised instantaneous energy values are then smoothed with a moving average filter of length 20, and forwarded to the audiovisual rendering blocks.

The Visual Rendering block creates a region $\{(x, y) \in \Re^2 | -1 \leq x \leq 1; -1 \leq y \leq 1\}$ within a window of 500 x 500 pixels, which is updated by a rate of 20 fps. Two objects are created within this region; a red disc of radius 0.1 (ball), and a blue square of sides 0.75. The centre of the square is translated to (0.625, 0.625) so that it resides at the top left corner of the region. The normalised alpha and beta energy magnitudes determine the coordinates of the red ball along the x and y-axes, respectively.

[1]http://biosig.sourceforge.net

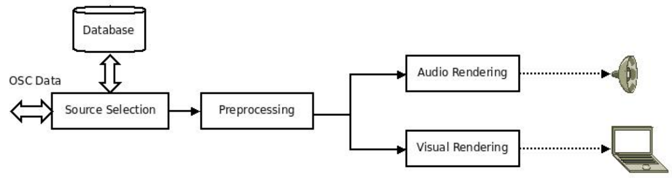

Fig. 7. Block diagram of $MiniBall\_EEG$.

The Audio Rendering block defines two sound generators, each generate the difference tones of two primitive waveforms. We have used two sine waves for alpha and two saw waves for beta band and tuned the difference tones to the centre frequencies of the corresponding band. These centre frequencies were 10 Hz (alpha) and 18 Hz (beta) in our experiment. The normalised alpha and beta values control the frequencies of the generators. For the alpha band, the mapping is defined by

$$f_\alpha = c_\alpha(2 - \bar{\alpha}) \quad (1)$$

where c_α is a scaling value. A similar expression gives f. We have used $c_\alpha = 32$ and $c_\beta = 4$. The normalised alpha and beta energy magnitudes determine the normalised gain according to $g = 0.25(|\bar{\alpha} - 1| + |\bar{\beta} - 1|)$ where $g \in [0, 1]$. This scaling ensures that the sound feedback becomes inaudible when the ball enters the target region.

We have experimented with two additional mapping strategies for rendering the alpha band only: the centre beating frequency and amplitude panning. The centre frequency is updated according to $f_{\alpha,c} = 10 - 2\bar{\alpha}$, the panning gains are set to

$$g_1 = (1 + \bar{\alpha})/2 \quad (2)$$

$$g_r = 1 - g_1 \quad (3)$$

for the left and right channel, respectively. In practice, these mappings are meant to sonify the coordinates of the red ball when there is no visual information available, e.g., when the subject closes his eyes.

The implementation of the $MiniBall\_EEG$ consists of a main control patch and visualisation window, as shown in Fig. 8. Once the data arrives and it is properly scaled, the feedback generation in the desired modalities (audio, visual, or audiovisual) can be switched on and off, and all the audio gains (alpha, beta, and the total mix) can be controlled in run-time. The goal is to move the red ball into the blue square. This translates to have brain activity in the alpha and beta bands simultaneously. We did not know how to construct a task description out of this goal; fortunately our participant is a neuroscientist, and he constructed his strategies himself: he dreamed of flying. The experiments took place in the last days of the workshop. While the quantitative analysis of the recorded data is still in progress, the primary observations indicate that our subject exhibited a surprising

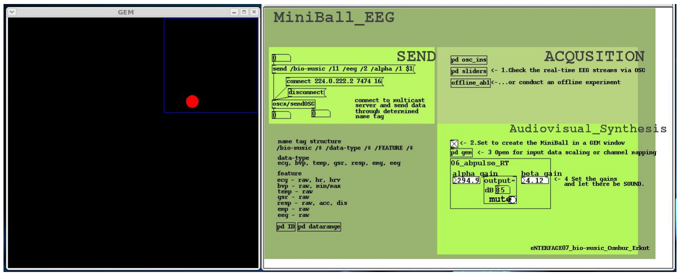

Fig. 8. $MiniBallEEG$ visualisation window (left) and control patch (right).

skill in regulating the alpha and beta bands, and enjoyed this skill trough the $MiniBall\_EEG$.

D. Conclusions and Future Work

In the future, we will implement automatic routing, online/offline selection, channel selection and mixing, and a data transmission port following the pre-processing or rendering operations in Source Selection block. We will determine the limiting values within the Pre-processing block by using the signal and the noise statistics. The current fixed-length of the moving-average filter can be made variable based on these statistics.

III. Three physiologically-driven artistic performances using the Bio-Music platform

In this section we describe the second approach which was used during the workshop the objective of which was the design of musical interfaces controlled by the physiological states of a performer. For this purpose, we set up a platform which allowed us to handle a large range of biosignals as typically used during psychophysiological monitoring (i.e. electromyogram (EMG), electrocardiologram (ECG), galvanic skin response (GSR), blood volume pulse (BVP), temperature and respiration signals). In the following sections, we first describe the *Bio-Music* platform developed during the workshop and then we present three artistic projects which resulted from the work within the project and which are built upon the Bio-Music platform.

A. The Bio-Music platform

1) Overview of the biosignals: In order to assess the physiological/affective state of the performer, we developed a hardware and software framework, we named *Bio-Music*, providing a range of meaningful features extracted from the class of biosignals we considered (Fig. 9). Here are some precisions about the biosignals we worked with in this project:

a) Electromyograms (EMG): Electromyography (EMG) is a technique for evaluating and recording physiologic properties of muscles: EMG measures the electrical potential generated by muscle cells at rest and while contracting. The resulting measured potentials range between 5 to 30 mV, and typical repetition rate of muscle is about 720 Hz, depending on the size of the muscle.

b) Electrocardiograms (ECG): Electrocardiography (ECG), aims at acquiring and processing the electrical activity produced by the beating heart. By means of two electrodes coupled sequentially out of the total number of electrodes wired to the patient, in order to create current loops between the acquisition interface and the human body, potential differences can be detected at several locations. Many techniques have been developed throughout history [25], the current one standardised for clinical applications requires 12 leads and allows the extraction of many features, even the reconstruction of the tri-dimensional electrical and displacement fields of the heart. We chose to use a technique derived from the "Einthoven triangular method", bearing the name of the scientist that introduced it in the early twentieth century, where in our case the three electrodes are not positioned on limb endings as the original protocol recommends, but closer to each others, thus housed altogether more ergonomically fixed on the chest. Our motivations in the choice of this setup are: cost-effectiveness, non-invasive ergonomics and feature extraction economy. The latter illustrates the fact that we found relevant to extract a small number of features, all of which allowing artistic applications, such as heart rate and heart rate variability.

c) Galvanic skin response (GSR): The galvanic response is a measure of electrical impedance of the wearer's skin surface, which reacts proportionally to emotional arousal i.e. stress level. The sympathetic system is responsible for activating the secretion of sweat on a person's hand or feet palms. The rise in surface sweat in turn increases the skin surface's conductance. GSR is typically measured with two skin surface electrodes placed on the palm side of two non-adjacent fingers. The baseline conductance levels, measured in Siemens, are person specific; however noticeable changes in GSR are generally seen in emotional states such as anger, fear, excitation, startle and sexual arousal.

d) Blood volume pulse (BVP): The blood volume pulse sensor uses photoplethysmography to detect the blood pressure in the extremities. Photoplethysmography is a process of applying a light source and measuring the light reflected by the skin. At each contraction of the heart, blood is forced through the peripheral vessels, producing engorgement of the vessels under the light source, thereby modifying the amount of light to the photosensor. BVP is measured with a sensor worn on the palmar side fingertip of the subject's non-dominant hand to minimise motion artefacting. Since vasomotor activity (activity which controls the size of the blood vessels) is controlled by the sympathetic nervous system, the BVP measurements can display changes in sympathetic arousal. An increase in the BVP amplitude indicates decreased sympathetic arousal and greater blood flow to the fingertips.

e) Phalange temperature: Phalange temperature is measured with a thermocouple fixed on the palmar side of one of the subject's fingers. The acral skin temperature experiences short changes related to the vasomotor activity of the arterioles. It is shown that the surface temperature of peripheral limbs vary as a consequence of blood flow [26].

f) Respiration: The respiration sensor is placed either over the sternum for thoracic monitoring or over the diaphragm

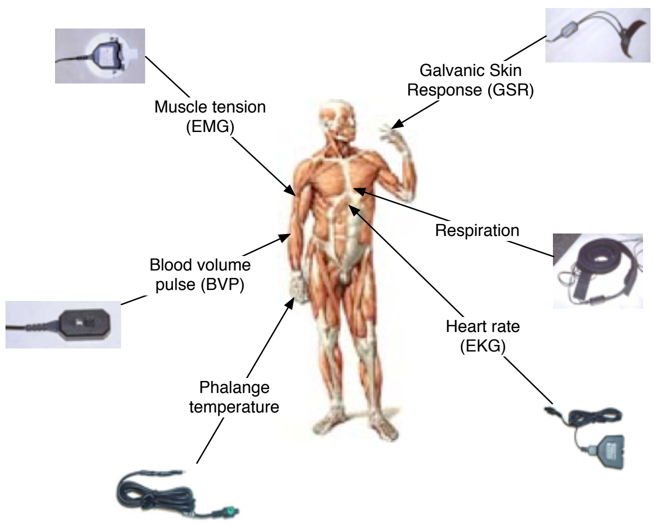

Fig. 9. Overview of the biosignals handled in the Bio-Music platform

for diaphragmatic monitoring. The sensor consists mainly of a large Velcro belt which extends around the chest cavity and a small elastic which stretches as the subject's chest cavity expands. The amount of stretch in the elastic is measured as a voltage change and recorded. From the waveform, the depth the subject's breath and the subject's rate of respiration can be learned.

2) Description of the two setups: The *Bio-Music* platform which we have developed is actually composed of two different configurations:

a) First setup: The first uses Thought Technology's ProComp Infiniti biofeedback system[2] capturing EMG, ECG, BVP, GSR, respiration and temperature signals, all sampled at 256 Hz. For the processing of these signals, we used the primary analysis functions provided by the manufacturer's software API. Further, we also developed a function allowing us to send the raw signals to Matlab and Python allowing us to use our own more complex processing tools (see Tab II). The sound and visual synthesis tools were implemented using the Max/MSP-Jitter[3] and Pure Data-GEM[4] software environments, which offer a large palette of sound and image processing tools for real-time artistic applications. The communication between all the software components of our platform rely upon the Open Sound Control protocol (OSC).

b) Second setup: The second hardware implementation we used consisted of two EMG sensor bands from Biocontrol Systems[5] which were connected to an Arduino[6] interface board with bluetooth networking. These hardware components interact with a computer running EyesWeb[7] software and a custom built patch for data acquisition. This setup provided a smaller number of biosignals but offered a more flexible and less intrusive way to measure muscle activity than the first setup. The analysis of the biosignals mainly consisted in this case of an envelope follower and was implemented within the same Max-MSP patch as the sound processing tools.

[2]http://www.thoughttechnology.com/proinf.htm
[3]http://www.cycling74.com
[4]http://www.puredata.org
[5]http://www.biocontrol.com
[6]http://www.arduino.cc
[7]http://www.eyesweb.org

TABLE II
FEATURES AND CHARACTERISTICS EXTRACTED FROM BIOSIGNALS

Feature	Characteristics
Statistical	Running analysis of mean, median, variance, standard deviation, minimum and maximum.
Rate of change	First and second derivatives.
Envelope detection	Using a low pass filtering algorithm.
Power spectrum	Power amplitude in selectable frequency ranges. Implemented with the Discrete Fourier Transform. The buffer length is adjustable, allowing control of spectrum accuracy.
Heart rate	Heart rate (HR), HR acceleration/deceleration

c) OSC Multicast: The *Bio-Music* platform is envisaged as potentially accomodating a wide variety of data acquistion hardware devices for the capture of biological signals which can then be sent to a wide variety of software applications for further processing. In order to receive data, from diverse sources, we decided to set up a multicast OpenSoundControl protocol server, which gives us flexibilty in having fast and direct connections between a number of sender and receiver clients connected to a local area network (Fig.10). OpenSoundControl[8] (OSC) is a protocol for communication between host computers, sound synthesizers and other multimedia devices which is optimised for modern networking technology. For this project, we defined our own proper OSC namespace, allowing to us to formalize a common way of exchanging data between the various components of the *Bio-Music* platform. During this workshop, a rich dataset has been collected and has been used extensively to implement and tune the signal processing functions of our Bio-Music platform. These datasets - and some illustrative video documentation - are freely available on the public project wiki[9]. Please also refer to appendices A and B for detailed descriptions of our OSC namespace and our biosignal datasets.

As an outcome of the artistic component of this project, we organised a Bio-Music performance night at a club in Istanbul where three musical and artistic performances utilising our platform were performed. The first one, performed by Koray Tahiroglu and Selcuk Artut was an improvisation for digital instruments controlled by electromyogram (EMG), galvanic skin response (GSR) and respiration signals. The second performance *Carne*, the result of a collaboratiion between the composer Miguel Angel Ortiz Pérez and the visual artist Hannah Drayson, was an interactive piece controlled by two EMG sensors. The last performance *Time Series* by Hannah Drayson was an investigation into subjective visualisations and sonifications of human emotions based upon measured biosignals. Each of these performances are described in the following sections.

[8]http://www.cnmat.berkeley.edu/OpenSoundControl/
[9]http://biomusic.wikidot.com

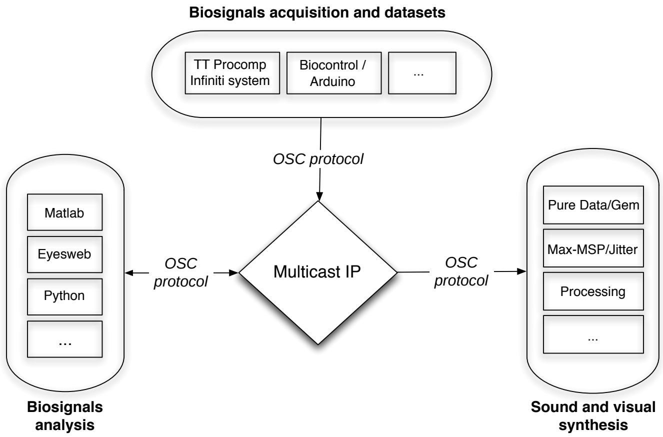

Fig. 10. The multicast OSC-based *Bio-Music platform*

B. Improvisation for Live BioSignals / various interfaces

This was an improvisation for digital instruments controlled by biological signals of two performers, Koray Tahiroglu and Selcuk Artut. Each performer was wired through different sensors in order to control and master their instruments during a real-time musical activity. This improvisation was a pure biological activity where there was an infinite joy and aesthetic pleasure. *Improvisation for Live BioSignals* aimed at achieving ever-changing unexpected sound structures and giving a chance to audience to recognise new possibilities in sound. Instruments that were driven by biological signals were created regarding to the characteristics of the signals.

One type of the biosignals used during the performance was the galvanic skin response (GSR), which measures the resistance of the skin to the part of a very small electric current. The magnitude of this electrical resistance is affected by immediate emotional reactions. In order to map the galvanic skin response changes, Selcuk Artut, who played a traditional bass guitar instrument during the performance, placed GSR sensors on his left index and ring finger. Higher or reduced arousal states of the body causes a change in the skin's conductivity; therefore, galvanic skin response sensor was used together with ECG sensor to control an instrument that created constantly dynamic rhythmic patterns.

Electrocardiography (ECG) measures the heart's electrical activity over time. Within the received data flow, rhythmic period of heart was mapped by detecting the peak levels for the each beat. Koray Tahiroglu positioned three ECG electrodes, two on the left and right side of the upper chest area and one on lower part of the rib cage closer to the heart. Changing patterns of the heart's electrical activity gave more chance to create a dynamic pattern with sound synthesis. Generating the common sonic representation of heart beat and ECG monitoring sound responses was avoid intentionally, instead noise sound sources were combined together with glitchy sound samples in order to create a rhythmic pattern. Heart beat structure could be traced in the sound structure. Glitchy sound samples, [sampleosccenter ˜] abstraction patch, were also controlled by galvanic skin response signals, so that rhythmic pattern that was constructed with [sampleosccenter ˜] and [noise4c ˜] abstraction was representing the overall heart beat activity of the two performers at the same time.

During the performance Koray Tahiroglu strapped the respiration sensor around the chest area and the measurement of the chest expansion was creating respiration signals. Respiration signals were easily controlled by producing different breathing patterns and this led Koray Tahiroglu to use respiration signals as a master controller for the overall sound structures in this improvisation process. Through this master control during the performance sonic structure of the improvisation process could be changed into three different modes.

1) Slow Respiration Mode: Slow Respiration mode activates the [sin3—- ˜] abstraction in a structure where pitch values changes in a higher frequency rate and modulation varies 0-8.50 out of 0-20 amplitude range. [sin3—– ˜] abstraction was created to control different sample position readings on a recorded sound material and also to have a modulation by sinusoid wave signs. Parameters of [sin3—– ˜] abstraction is set through drunk walk probability method. Simply producing a slower breathing pattern and keeping the chest expansion in a lower state can keep the sonic structure of the improvisation in the slow respiration mode. [instr6] abstraction is the polyphonic sound synthesis of different sound samples driven by Electromyography (EMG) sensor. EMG measures muscle response or electrical activity in response to a nerve's stimulation of the muscle. First EMG sensor was taped on the inner side of the right arm of Koray Tahiroglu and by moving his right wrist and his arm itself, it was possible to change the pitch information of the related sound sample. Master control through respiration signals also change the sound sample type in [instr6] abstraction into three different modes. Slow Respiration mode sets a sound sample, which responds with continues long and no sudden changing structures in polyphonic synthesis.

2) Normal Respiration Mode: In this mode, [sin3—– ˜] abstraction generates a continuous low frequency pitch. Without changing the pitch value, only modulation parameters are generated between the range of 1.63-4.48 over 0-20 amplitude range through drunk walk probability method. Keeping the constant pitch information created a low frequency wall sounds with different modulation varieties. On the other hand normal respiration mode set a rhythmic sound sample in [instr6] abstraction, and by changing the right arm's muscle activity it was possible to control the pitch values of the second sound sample.

3) Fast Respiration Mode: Fast respiration mode modulation was set at 0.807 amplitude levels; however, pitch values were dynamically created through drunk walk probability method with [sin3—– ˜] abstraction. [instr6] abstraction was creating heavy noise based structures with low frequency and glitchy sounds. This level was meant to be creating a chaotic sonic structure regarding to the noise based music.

EMG sensors had been used as a controller for [instr6] abstraction patch. The pitch values of sound samples with applied polyphonic sound synthesis within their related mode structure was controlled by the performer. Koray Tahiroglu also taped a second EMG sensor on the inner side of his left arm. He used the second EMG signals to control the

Fig. 11. Miguel Angel Ortiz Pérez performing *Carne*

instruments on and off situations. Related to the improvisation, with the second EMG signals some instruments could be turned off and some instruments could be turned on. This second main controller gave a chance to decide which one of the instruments should play together at the certain stage of the improvisation. Except the EMG sensor's signals, GSR, ECG, respiration had continuous streaming signals, because all were related with continues heart beat and respiration activities; therefore, there had been a need to control the instruments current on/off situations during the improvisation.

C. Carne

Carne is an interactive piece for two EMG sensors. It was composed as part of the activities on the eNTERFACE summer workshops '07. It was premiered at the Boğaziçi University Music Club on August 8 2007. The piece is an audiovisual collaboration between Miguel Angel Ortiz Pérez (interface and sounds) and Hanna Drayson (visuals). Fig.11 shows the performer at the premiere.

1) Piece concept: *Carne* is loosely inspired by Terry Bison's 1991 short story *"They're made out of meat"*[27]. The concept behind *Carne* is based on a very simplistic view of muscle activity as the friction between slices of meat. Taking this idea further, we could say that all types of arms movement from minimal arm gestures up to the highly complex synchronised movements of fingers during musical instrument performance, are simple variations of this meat grinding activity.

The sounds in *Carne*, evolve inside a continuum from imaginary muscle sounds to pre-recorded sounds of western bowed string instruments, while always keeping focus on friction as a unifying metaphor.

2) Piece architecture: This piece used the second setup of the Bio-Music platform, relying on the Biocontrol Systems unit and an EyesWeb data acquisition patch. EMG signals are then transferred in real-time through OSC protocol to a second computer running a slightly hacked version of the CataRT[10] application by Diemo Schwarz [28]. Within this patch, a large database of samples are loaded, analysed and organised using psychoacoustic descriptors. The resulting sound units are laid on a two-dimensional descriptor space where the X axis represents noissines and the Y axis represents pitch. The EMG signals from each arm controls movement on one of these axes. The values from the EMG are dynamically scaled throughout the duration of the piece, allowing the performer to explore cluster areas of the sound corpus and giving a sense of structure and evolution to the piece.

[10]http://imtr.ircam.fr/index.php/CataRT

D. Time Series; an uncontrolled experiment

This performance was presented by Hannah Drayson (experimenter/performer), Mitchel Benovoy (data acquisition) and Christian Mühl (subject) during our Bio-Music night session. The initial work on this piece evolved from an early investigation into capturing physiological data related to emotion and psychophysiology. The Thought Technology ProComp unit was used to capture six datasets consisting of five physiological signals, i.e. blood volume pulse, galvanic skin response, temperature, respiration and electrocardiogram. In order to stimulate various emotional states, the subject sat quietly and attempted to describe in writing a number of memories of experiences which correlated with the desired emotions. The texts were marked every 30 seconds to allow them to be aligned with the data recordings. The emotion datasets consisted of sadness, joy, anger, depression, calm and pain.

For this performance, we designed a Pure Data patch that transforms these emotion datasets into sounds and visuals. The final output of this patch was a three dimensional sphere built from rotating disks, whose direction and speed of spin was dictated by the incoming physiological signals. Each signal was also attached to a specific oscillator audio object, and as a group create a constantly evolving range of tones.The resulting visuals and sounds were projected and amplified, allowing the audience to experience the subjects data re-interpreted in real-time. Hannah Drayson presented a number of experiments on the subject, Christian Mühl. These were four light hearted 'multimodal' sensory experiences, with the aim to provoke observable physiological change in the state of the subject, and to take advantage of the 'non-scientific' experimental setup to try slightly absurd and fun combinations and stimuli. These stimuli consisted of:

- Standing with your back to a room full of people while they all stare and point at the back of your head. The subject was asked to stand with his back to the room, and the audience were invited to stare and point as hard as they could.
- Relaxing and eating cake. The subject was seated in a large comfortable armchair, and given a box of baklava to eat.
- Drinking beer and looking at kittens. The subject was given a cold can of beer to drink and asked to look at kittens, there was also a young cat sleeping on a chair in the performance space which was brought the the front to be looked at.
- Having all your arms and legs pulled by your friends. Members of the audience came forward and took hold of a limb each and pulled on the subject.

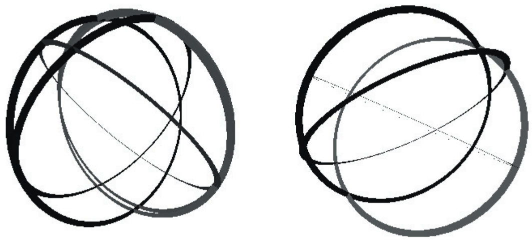

Fig. 12. Three dimensional sphere built from rotating disks, whose direction and speed of spin is dictated by the incoming physiological signals.

During the experiment changes in the auditory and visual signals were observed, one audience member remarked that at one point the sonification had sounded 'a bit like a whale'. Whilst the performance itself was lighthearted, it forms part of larger project and observation of the limits of human machine interaction, in that gestalt states such as emotion are easily observed by other humans, but extremely hard to define simply in terms of physiology. One interesting finding of this work is that highly abstract representations of a subject data could still reveal emotional states to human observers, and in fact give greater intimacy with physiological changes which are not overtly manifest in everyday contact.

IV. Conclusion

In this paper we have surveyed some approaches which are possible in using biological signals as control sources to generate computer synthesis parameters for visual or auditory displays. We have also here presented some techniques, strategies and methods for using biological signals as motive forces for use in ongoing biologically generated visual, sound and music experiences. We feel we have introduced some innovative and useful techniques and expanded upon other established ones which will help give rise to nascent explorations as well as further ongoing research in this important yet less-travelled area of scholarship. We look forward to criticisms, additions and engagements from other interested parties who could help to further the goals of an open-source, free and functional system for the treatment of biological signals as meaningful drivers for sonification and visualisation processes.

Hopefully, we have also shown that there are diverse signal processing techniques which can be applied to raw biological signals, which, in due course, may help us to understand the semantics of their ontologies. The sonifications or visualisations of these signals may have the functions of scientific, medical, clinical or artistic expressions. The final manifestation is more a matter of end-use than method. We would hope that all potential methods for treating biological signals might be considered as useful to those who are engaged in this field, be their domain science, medicine or the arts.

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APPENDIX A
DATA TRANSPORT PROTOCOL
(OSC OVER UDP MULTICAST)

The *Bio-Music* system is envisaged as potentially accommodating a wide variety of Data Acquisition (DAQ) hardware devices for the capture of biological signals which could then be sent to a wide variety of software (and potentially hardware) applications for further processing or display. Biosignal sensors require certain type of interfaces and software; in principle, the biosignals would be the only sources whilst other applications that consume this data would be sinks but could in fact also be sources of processed data analyses etc. Using OpenSoundControl over UDP multicast was a very specific design decision: practically it was not possible to run each sensor type with each computer during the workshop, not only because of operation system dependencies, but also because of computers data processing efficiency. In order to receive different data types from different sources, setting up multicast open sound control protocol server became an agreed alternative, which can maintain fast and direct connections between sender and receiver.

Open Sound Control (OSC) is a User Datagram Protocol (UDP) network based protocol for communication among computers with a low limitation on latency, which is optimized for modern networking technologies. It uses a URL style syntax to specify instructions or data for specific uses. OSC allows the user to define a namespace for their particular application purpose. OSC also supports Unix-style file globbing and pattern-matching mechanisms so that sophisticated and fine-grained selections can be made (similar to regular expressions). It is very network-friendly but is not tied to any one transport protocol, i.e. it could use TCP/IP as well as IEEE 1394/Firewire. Additionally, and very importantly, OSC is already supported by a wide range of hardware and software applications. Also, the bundle mechanism allows multiple messages to be sent with tone given time-tag so that all events can occur at the same time. Even through OSC protocol, users can interact clearly with the networked computers; however, regarding to the server-client communication type of the project, OSC based multicast server was chosen to be used as a communication protocol in local area network. The advantage of using multicast server is the possibility to transmit the same data to more than one host, and instead of broadcasting, only related host is receiving the message and the message is transmitted only once for many clients, which saves a lot of bandwidth in the network[11].

[11] http://www.tack.ch/multicast/

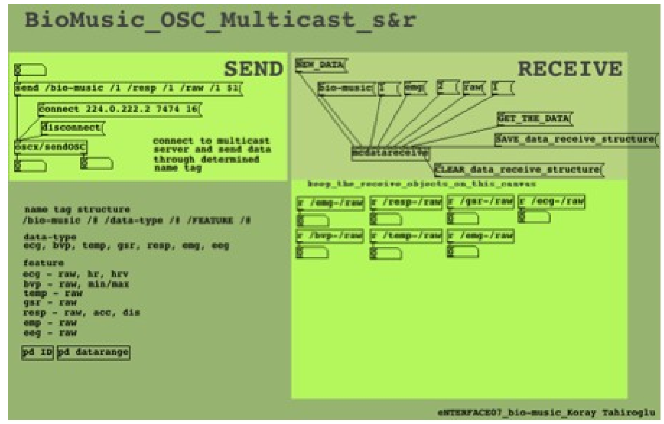

Fig. 13. Snapshot of the OSC Multicast Pure Data patch

Building OSC multicast structure required defining the project name tags, which must to be specified by the sender and receiver for the requested data types. For the purpose of this project, we defined our own OSC namespace characterized thus: /bio-music/#/source/#/type/#/. As an example, a typical bio-music OSC message could look like this: /bio-music/3/eeg/2/coherence/2 ...DATA....DATA.... which would indicate that we have 2 channels of 'DATA' from subject 3's EEG which is indicating coherence in their EEG. A Pure Data patch has been designed to automatically manage the formatting of OSC messages sent and received between each components of the *Bio-Music* platform (Fig.13).

All devices (host computers, servers, capture stations etc.) are connected to a local network, preferably using 100baseT or gigabit ethernet, which has UDP multicast enabled, as most LANs do. In principal, all nodes can act as sources and/or sinks although in most cases they will be one or the other. Some method of auto-discovery for the bio-music nodes is preferred (could likely be the ZeroConf protocol) such that namespace collisions can be avoided whilst also allowing bio-music nodes to discover each other and auto-configure themselves. Some possible bio-music nodes could include:

- biosignal source
- DSP analysis
- server stockage of data (recording)
- sonification or music output
- visualisation of visual artistic output

So, in a sense, all nodes on the bio-music network can provide and have access to any information simultaneously if they wish. Sampling rate of biosignals are fairly low (64 - 256 Hz typically) and thus it seems that issues of data collisions, timing and jitter on the network should not be significant if a fast and reliable ethernet LAN is used.

APPENDIX B
BIOSIGNALS DATASETS COLLECTION

A rich dataset was collected using GSR, BVP, ECG, phalange temperature and respiration signals and was extensively used to implement and tune the signals processing functions. Dataset generation was conducted in a quiet, comfortable lab environment. The subject either remained seated or standing and was instructed to limit his body movement to minimize motion artefacts in the collected signals. The biosignals were recorded using Thought Technologys ProComp Infiniti biofeedback system all sampled at 256 Hz. Two types of scenarios where recorded: emotional states and electrical muscle activity. The different emotional state data permits training and classifier validation of online affective state recognition. Emotions were elicited using self-generation such as event recollection and personally chosen music listening. As for the muscle activity, four sites were selected while a musician performed on an accordion: bicep, pectoral, forearm and calf muscle activity was measured in synchronous with video recording. Here is a report of a biosignals-based emotional state recording session achieved during the project:

Biosignals Dataset v.0.1
Date of collection: 23/07/07
Acquired by: Mitchel Benovoy
Environment: Air conditioned lab, noisy

- Subject
  - Gender: female
  - Age: 26
  - Background: English, artistic training, Ph.D student
- Acquisition interface
  - Hardware: Thought Technology ProCom Infinity
  - Software: Biograph Infinity
  - Signals acquired: GSR, BVP, ECG, Temp, Resp
  - Signal characteristics: raw
  - Sampling rate: subsampled at 256 Hz
- Number of trials: 6
  - Elicitation paradigm: Past event recollection (emotionnally charged), subject used hand writting as expressive aid.
  - Emotions/states captured: sadness, joy, anger, depression, relaxation, physical pain
- Trial specifics
  - Trial 1.xls: sadness
  - Trial 2.xls: joy
  - Trial 3.xls: anger
  - Trial 4.xls: depression
  - Trial 5.xls: relaxation (using breathing techniques)
  - Trial 6.xls: pain (cold water drinking with wisdom tooth pain)

File format: Excel worksheets. column separated.