LISTENING TO THE MIND LISTENING: SONIFICATION OF THE COHERENCE MATRIX AND POWER SPECTRUM OF EEG SIGNALS

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1. INTRODUCTION

In this paper, we present our strategy for sonification of EEG signals as part of the 'listening to the mind listening' project [1]. It is generally thought that similarities between EEG signals recorded at two distinct points on the scalp indicate that the brain is performing the same task at these two points. A high correlation coefficient can be used as an indicator of such similarities. Using EEG data supplied by project coordinators, we have created a coherence matrix representing levels of similarity between 26 electrode signals. A new coherence matrix was calculated for every one second time frame of the EEG data. In order to focus on the true significance of the data some pre-processing was applied on the original EEG data before this matrix was created. Our sonification approach then aimed at representing the correlation coefficients of the coherence matrix.

From the the EEG data we also extracted and sonified the level and position of delta, theta, alpha and beta waves which indicate various states of brain activity (e.g. alertness, sleep, relaxation, etc.). Alpha waves (7-13Hz) were most prominent in the data. Alpha activity corresponds to a relaxed state suggesting that the subject was most probably in a stationary sitting position with eyes closed while the EEG recording was being made. We were also able to detect other brain activity in the delta, theta and beta frequency bands and locate regions of this activity. Our sonification combined activity in these frequency bands with other aspects of the coherence matrix. We decided to use only the 26 first electrode signals in order to focus directly on activity within the brain.

We first explain the need for data pre-processing. We then briefly overview our sonification software architecture, and finally present our sonification strategy for the coherence matrix and brain activity in the four low frequency bands.

2. DATA PRE-PROCESSING

We first removed the DC offset using a DC blocking filter [2]. We then performed a spectrum analysis of the 500Hz sampled original data. Although this was sampled at 500Hz we observed that the most useful information was concentrated in the lower part of the spectrum (below 25Hz) (Fig. 1). Data was then resampled at a lower sampling rate of 50Hz allowing us to 'zoom in' on this information (Fig. 2). The dense band shown in Fig. 2 corresponds to activity in the alpha band.

We note that additional pre-processing might have been applied to eliminate noise introduced by muscular activity and recording artifacts during the EEG recording. However this noise did not prove to be a problem and we proceeded without needing to remove it.

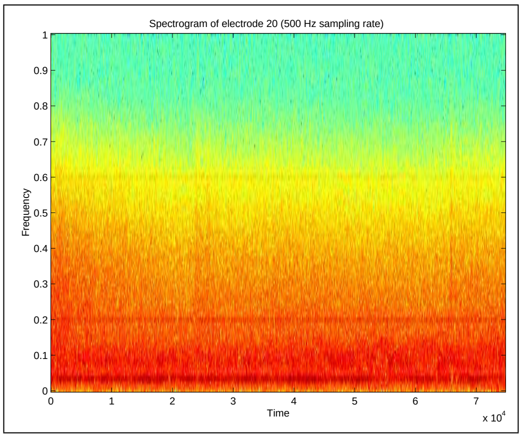

Figure 1: Spectrogram of electrode 20 (original data)

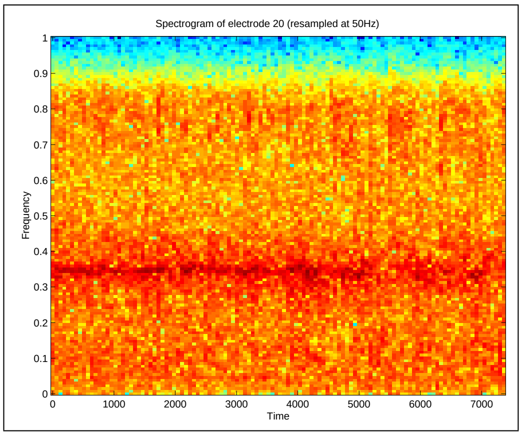

Figure 2: Spectrogram of electrode 20 (50Hz sampling rate)

3. SYSTEM OVERVIEW

Matlab was used to extract features from the pre-processed data. The following features were extracted: correlation coefficients between each pair of electrode, RMS power per each electrode, global RMS power, mean of all correlation coefficients. These variables were calculated for every 1 second of data read. A Matlab script was also developed to produce a CSound score in numerical score format (Fig. 3). This was used with a separately created Csound orchestra file to synthesise audio. CSound rendered audio directly to disk as a 26 channel audio file, one channel for each electrode. Finally Max/Msp (Fig. 4) was used to spatialise each of the 26 electrodes to their respective position in the target speaker configuration. Spatialisation was implemented in Max/Msp using a vector based amplitude panning algorithm called VBAP [3].

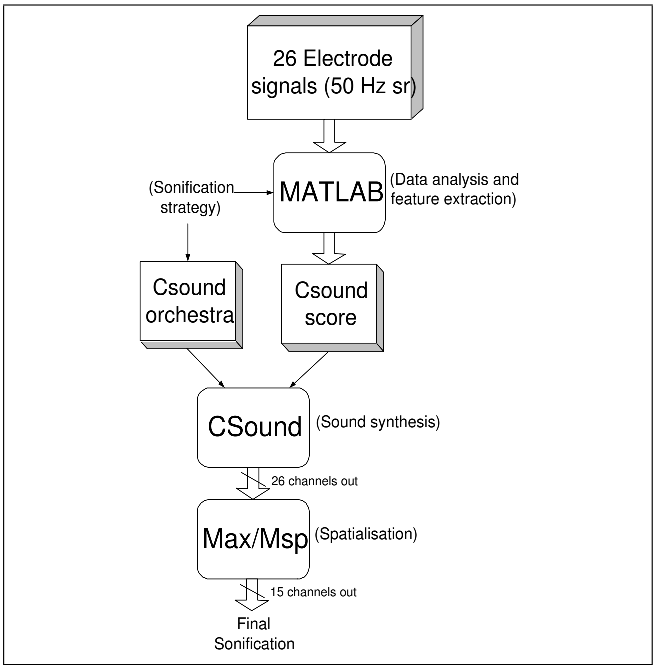

Figure 3: *Sonification system overview*

4. COHERENCE MATRIX

The coherence matrix contains the correlation coefficients between any pair of electrodes (Fig. 5). Correlation coefficients are scaled from -1 for signals that are exactly similar but 180 degrees out of phase, 1 for exactly similar signals that are in phase and 0 for totally dissimilar signals. On average we found that correlation between electrodes was fairly high, around +0.8/0.9 as shown in (Fig. 5).

For 26 channels, the correlation matrix represents unique correlation coefficients. Each of the 26 electrodes can be combined with 25 other electrodes to give a total of 325 combinations. We calculated new matrices of correlation coefficients for every 1 second of EEG data. This allowed temporal changes in the synchronisation of different parts of the brain to be observed more easily. Our objective in the sonification was to represent 300 matrices of 325 coefficient during the 5 minute duration of the EEG data

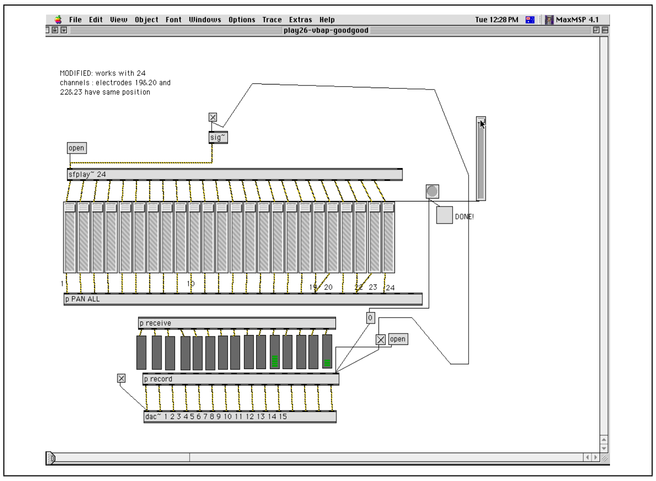

Figure 4: *Spatialisation of 26 sound sources (electrodes) using Max/Msp*

recording. While the data initially seemed to be excessive, the most significant correlation values were identified as those where the value of correlation coefficients exceeded 0.9. We decided that our sonification of this correlation matrix should focus a listener on the level of correlation between two electrodes and the position of these electrodes. To do so we choose to represent the correlated pair as two short sounds in succession, using the correlation value to control their timbre and loudness. The first of the pair is played at the first electrode position then repeated after a delay of 0.4 s at the second electrode position. In this way a listener may perceive correlation between the two points. For this purpose, drum like sounds were created using the 'pluck' opcode of Csound.

The effectiveness of this sonification largely depends on the listener's ability to match two sounds that have the same correlation value for these two electrodes and the listener's acuity in sound localisation. The loudness and timbre of the drum-like sound was controlled so that events with high correlation values could be differentiated from events with lower correlation values. Extremely high correlation values can be easily from all the others.

Another aspect of this sonification design that became apparent to us only at a later stage is that since correlation coefficients below 0.9 are not sonified, a high density of drum like sounds at a given time indicates a high level of global coherence of the subject brain at this time. In the sonification piece, sections with low and high densities of drum like sounds can be clearly perceived, indicating fluctuations in the global coherence of the subject brain.

5. RMS SPECTRAL POWER AT ELECTRODES

This aspect of our sonification aimed to represent the level, position and variations in the region of highest activity in four low frequency bands (delta, theta, alpha and beta). The region of highest activity is defined as the region which has the highest RMS power for a given time-frame of 1 second. A tool for Matlab called EEG Toolbox [4] was used to visualise regions of highest activity. Fig. 6 shows a topographic map of the scalp surface with regions of highest activity (i.e. RMS value), in this case an electrode placed on top of the head (Cz) is within the region of highest activity (shown here as a narrow light region that radiates in one direction from the

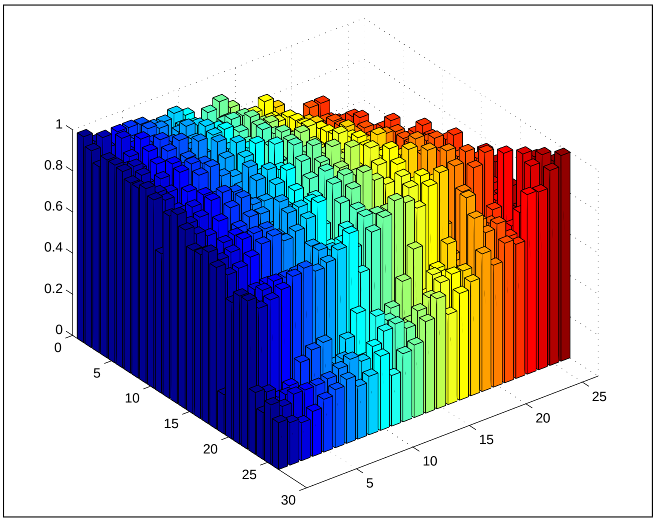

Figure 5: *Coherence Matrix of 26 electrode signal (1s time frame)*

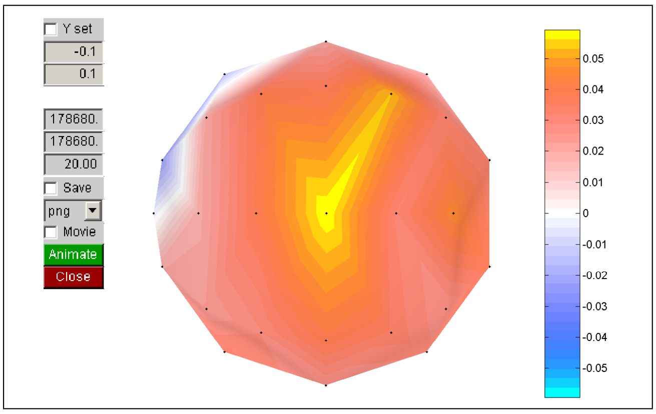

Figure 6: *Topographic map of electrode potentials*

centre).

In order to measure the RMS power for each frequency band it was necessary during preprocessing to filter the 26 electrode signals with brick wall band pass filters. An RMS power measurement was then performed for every time frame of 1 second. Using Matlab we then located electrodes with the highest RMS values for a given time frame. We also calculated the global RMS power of all electrodes (Fig. 7).

These values were then used to generate a CSound score based on the position and power of the electrodes with the highest RMS power (for each of the four frequency bands) for every 1 second frame. Using this score, an audio file was synthesised using Csound.

The positions of electrodes with the highest power were also saved as a separate text file. This file was then read by Max/Msp which overlaid dynamic spatial trajectories onto the synthesised audio file. The sound synthesis process is described below.

5.1. Sound synthesis

Brain activity in the four low frequency bands was represented as variations in the amplitude of sustained harmonics. This variation

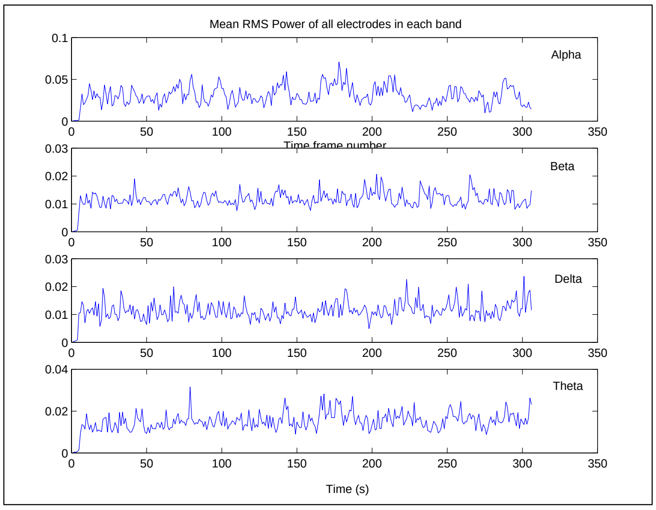

Figure 7: *Global RMS power in each frequency band*

was accomplished by detuning four groups of oscillators to produce audible flanging effects at four independent rates. Each of the four groups was detuned using one the four signals representing delta, theta, alpha and beta waves.

This effect is based on Risset's glissando instrument [5] which detunes all but one of a group of nine oscillators, where each waveform is the sum of a number of harmonics and where a microtonal interval is used to detune each of the oscillators to produce a chorus effect. Each instrument was configured to respond to fluctuations in the RMS signals that represent alpha, beta, theta and delta waves. These fluctuations affect the size of the detuning interval which in turn affect the rates of beating in each chorus of oscillators. This differs from Risset's instrument, which uses a fixed detuning interval. Each wave form also uses a different set of harmonics as shown in Fig. 8. We created four waveforms by selecting harmonics to approximate a minor chord with some added intervals. By starting at different points along the harmonic series we produced wave forms with identical octaves and fifths together with a variety of just thirds and seconds. Differences in the spacing between harmonics were used to create subtle variations of intonation. The lowest audible harmonic in each waveform is 55 Hz. The fundamental of each of the wave forms is set to one of the frequencies shown in Fig. 8.

	Harmonics	Fundamental
Delta	11 22 33 44 52 60 66 74 88	5.0 Hz
Theta	7 14 21 24 28 33 42 50 56 64 68	7.857142 Hz
Alpha	5 10 12 15 17 20 24 30 34 40 48 56	11.0 Hz
Beta	3 6 9 12 14 18 20 24 26 28 36	18.333 Hz

Figure 8: *Harmonics and fundamental frequencies used to represent sub-audio brain activity*

6. CONCLUSIONS

Our sonification used only a small part of the information present in the EEG data. Because the process is only a musical metaphor for what happens in the mind of a listener we decided to make the metaphor as musically interesting as possible. It was necessary to limit the amount of information we used and focus on essential information about the data set. Localising points of correlation in a coherence matrix was one way of doing this; representing brain activity taking place at sub-audio rates was another. Like effective graphic representation the amount of information can be reduced if it can be distilled or reorganised as higher order information.

7. REFERENCES

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