# SONIFICATIONS FOR EEG DATA ANALYSIS

*T. Hermann · P. Meinicke · H. Bekel · H. Ritter*

*H. M. Müller*[1] *· S. Weiss*[2]

Faculty of Technology
Bielefeld University, Germany
{thermann|pmeinick|hbekel|helge}
@techfak.uni-bielefeld.de

[1]Faculty of Linguistics, Bielefeld University, Germany
hmueller@uni-bielefeld.de
[2]Brain Research Institute, University of Vienna, Austria
sabine.weiss@univie.ac.at

**ABSTRACT**

This paper presents techniques to render acoustic representations for EEG data. In our case, data are obtained from psycholinguistic experiments where subjects are exposed to three different conditions based on different auditory stimuli. The goal of this research is to uncover elements of neural processing correlated with high-level cognitive activity. Three sonifications are presented within this paper: *spectral mapping sonification* which offers a quite direct inspection of the recorded data, *distance matrix sonification* which allows to detect nonlinear long range correlations at high time resolution, and *differential sonification* which summarizes the comparison of EEG measurements under different conditions for each subject. This paper describes the techniques and presents sonification examples for experimental data.

## 1. INTRODUCTION

Electroencephalogram (EEG) studies are able to provide electro-physiological data about the brain's activity. Within the project "cortical representation and processing of language" (SFB 360) at Bielefeld University, the aim is a neurophysiological analysis of the functional behavior of participating neuronal assemblies during high level cognitive processes with a focus on language comprehension. Classical analysis techniques are event related potentials (ERP) and coherence studies [1]. As a rather new approach, sonification of EEG data is now considered as a means of assisting and accelerating data inspection, pattern classification and exploratory data analysis.

Previous work on the sonification of EEG data was done by Mayer-Kress [2]. However, for sonification, he mapped activation directly to musical pitches of musical instruments which allowed only to present short signal parts in a reasonable time. Another type of EEG data sonification known is the audification of EEG data [3]. Here, the usually very noisy signals are played either without modifications or by applying frequency modulation to shift them into a suited frequency range. However, these sonifications are mainly applied for real-time monitoring (e.g. in bio-feedback systems) and are not suitable for an exploratory data analysis.

In this paper, three sonifications are developed which provide a means for the fast inspection of short-time Fourier transform spectra from the measurements. *Spectral Mapping Sonification* allows frequency-selective browsing of EEG data. *Distance Matrix Sonification* allows to follow the time-variant distance matrix of the spectral vectors. *Difference Sonification* allows to summarize the results of a comparison of data for one subject under two conditions in an auditory scan through the brain.

## 2. EXPERIMENT AND DATA

This work was based on a previously collected data set [4, 5] In this experiment, 25 female participants, aged 20 to 30 years, were seated in a sound reduced chamber and asked to listen to auditory presented stimuli that were presented via headphones. Among the several stimuli there are three sets which are used for the current sonifications:

(i) Spoken Language (story) with Austrian-German speaker (mean duration 2 min),

(ii) Pseudo Speech, which consists of auditory patterns generated by amplitude and frequency modulation using a base frequency of 200 Hz and an amplitude envelope which resembles the real spoken sentences, and

(iii) EEGr, where the EEG is recorded for 2 minutes during rest with open eyes.

The three conditions were chosen in order to identify patterns which emerge from the higher-level cognitive processing of speech rather than from the acoustical analysis of the stimuli. Different spectral bands are discerned while analyzing EEG data, which are supposed to play specific functional roles, namely the $\delta$-band (1-4 Hz), $\theta$-band (4-8 Hz), $\alpha_1$-band (8-11 Hz), $\alpha_2$-band (11-13 Hz), $\beta_1$-band (13-19 Hz) and the $\beta_2$-band (19-30 Hz). Former data analysis [4, 5] indicated that the $\alpha_1$-band reflects processes of acoustical analysis whereas the $\beta_1$-band reflects cognitive components.

The EEG data were recorded with 19 scalp electrodes positioned according to the international 10-20 positioning system, measured against the averaged signal of both ear-lobes. Prior to analysis, the signals were band-pass filtered (0.3 Hz to 35 Hz) and digitized using a 16 bit quantization and a sampling rate of $\nu_{SR} = 256$ Hz. Figure 1 gives an overview of the available electrodes as well as their positions on the scalp and further shows some typical time series for selected electrodes.

## 3. SPECTRAL MAPPING SONIFICATION

The simplest approach to get an acoustic representation of EEG data is to use audification, the direct playback of the raw time series as air pressure variations. The main problem with audification is that the resulting sound is very noisy and independent control over playback speed and pitch is difficult. Some EEG data audifications are illustrated in Table 1. All sound examples can be found on our web site [6]. Two channels (Fp1 and channel T5) are audified for three subjects (S1–S3) and all conditions. Playing the Fp1 audification on the left and the T5 audification on the right audio
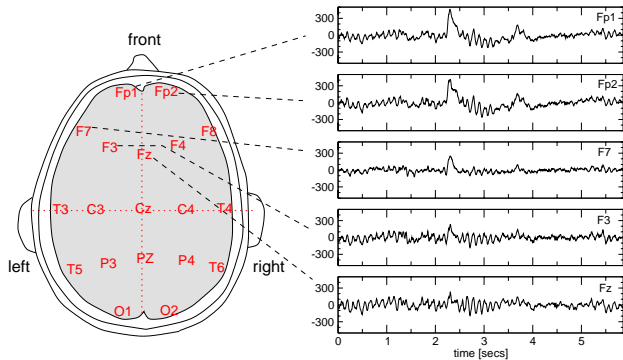
Figure 1: Illustration of the available EEG electrodes and their position on the scalp. Some typical data series are shown on the right. Left picture after [7].

channel allows to compare the temporal evolution of both signals and to detect time-dependent correlations. Obviously, the audifi-

| Sound: | S1 | EEGr: Fp1, T5, Fp1/T5. speech: Fp1, T5, Fp1/T5. pseudospeech: Fp1 |
|---|---|---|
| | S2 | EEGr: Fp1, T5, Fp1/T5 speech: Fp1, T5, Fp1/T5. pseudospeech: Fp1 |
| | S3 | EEGr: Fp1, T5, Fp1/T5. speech: Fp1, T5, Fp1/T5. pseudospeech: Fp1 |
| Duration: | | $\approx 2$ sec |

Table 1: Sound Examples for Audification of EEG data for subject S1–S3.

cations sound very noisy. In this noise some strong low-frequency bursts can be perceived. Some of these are artifacts caused by muscle activations. As the sound amplitude is normalized to the available quantization range, different audifications have a different level. Here, an outlier elimination is crucial before using audification. However, audification is a fast method to locate such outliers manually.

But aside these dominating sound elements, in some audifications specific pitched patterns are perceived, e.g. in (S3-speech-T5). Here, three pitched bursts occur with decreasing pitch. These pitches correspond to activity within the $\alpha_1$-band. Besides this, interesting acoustic features can be perceived in (S1-EEGr-Fp1): 4 short pitched events with a down chirp pitch curve. The pitch corresponds to peaks within the $\beta_1$-band. Such features are more easily detected from the sound than from the extremely noisy time series plots and even in spectrogram plots these chirps can hardly be seen (see Figure 2).

The main problem of audification is, that independent control on the spectrum and duration is limited. Therefore, the presented sonification technique uses the short time Fourier transforms (STFT) of the time series as starting point. Given the measurements $s_i[n]$ where $i = 0, \ldots, 18$ determines the channel and $n$ is the sample number, the STFT is computed for each channel $i$ by

$$\tilde{s}_i[m, k] = \sum_{n=0}^{N-1} s_i[Cm + n] w[n] \exp\left(-i\frac{2\pi nk}{N}\right) \quad (1)$$

where $m$ is the frame number, $C$ the offset between succeeding frames, $k = 0, \ldots, N/2$ the frequency index and $N$ the window width in samples. For the following sonifications, a triangular window $w[n]$ is used. The value $|\tilde{s}_i[m, k]|$ denotes the frequency amplitude at frequency $f(k) = k\nu_{SR}/N$, $k \in \{0, 1, \ldots, N/2\}$ in the $m$th frame, including the samples $[Cm, Cm+1, \ldots, Cm + N - 1]$.

A compromise between coarse frequency resolution for small $N$ and coarse time resolution for large $N$ must be found. For further analysis $N = 256$ is chosen corresponding to an anaylsis window of 1 sec. Figure 2 shows spectrograms for different electrodes for one subject.
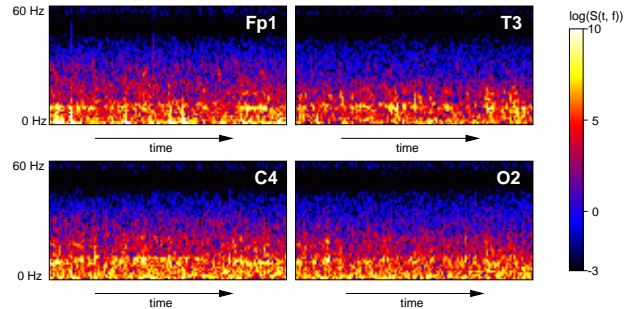


Figure 2: Spectrogram of measurements for 4 channels, shown for one subject and the EEGr condition for 64 seconds data. The color is given by $\log(\tilde{s}[m, k])$. High energy pattern within the $\alpha$-band can be seen in the plots.

After this pre-processing, 19 spectrograms are given. The EEG sonification by spectral mapping now superimposes for each selected electrode $i$ a set of $N_{osc}$ time-variant oscillators whose frequency $f_n$ for $n = 0, \ldots, N_{osc} - 1$ is given by

$$f_n = \ln(2) \exp\left(p_{min}^o + \frac{n}{N_{osc} - 1}(p_{max}^o - p_{min}^o)\right) \quad (2)$$

where $[p_{min}^o, p_{max}^o]$ denotes the desired output pitch range in octaves. Let $\tilde{s}_i^k(t)$ denote the time-variant function from interpolating the sequence $\tilde{s}_i[0, k], \ldots, \tilde{s}_i[M, k]$ such that $\tilde{s}_i^k(0) = \tilde{s}_i[0, k]$ and $\tilde{s}_i^k(T) = \tilde{s}_i[M, k]$. Then the amplitude of the $i$th oscillator is given by

$$a_i(t) = \hat{a} g_\delta\left(\frac{\tilde{s}_i^k(t)}{\max_{t'} \tilde{s}_i^k(t')}\right) \quad (3)$$

where $g_\delta(\cdot)$ is a nonlinear function which suppresses all amplitudes less than a given threshold $\delta$.

Only few parameters need to be specified for sonification, namely the duration per frame $T_f$, the pitch range $[p_{min}^o, p_{max}^o]$ and the EEG frequency range.

With this sonification, the activity in a specific spectral band can be monitored. Assume, we are interested in the $\alpha$-band from 8 Hz to 13 Hz. As the window width is 1 sec we have a frequency resolution of 1 Hz and thus 6 frequency cells are within the selected range. Thus 6 time-variant oscillators are created which monitor signal energy as loudness. Suited time compressions are about 50, allowing to monitor 50 seconds of experimental data in 1 sec. If more than one channel is of interest, the sonifications of chosen channels can be superimposed. To compare different

regions, each channel can be assigned to the left or right stereo channel. Some example sonifications to illustrate the sound are presented in Table 2. The threshold $\delta$ allows to control the com-

| Sounds: | $\delta = 0.4$, 0-30 Hz, left: T3 T5 right: T4 T6 |
|---|---|
| | S1, S2, S3, S4, S5, S6 |
| | $\delta = 0$, 0-30 Hz, left: T3 T5 right: T4 T6 |
| | S1, S2, S3, S4, S5, S6 |
| | $\delta = 0$, 0-30 Hz, (sounds for S1–S6) |
| | left: F7 F3 T3 C3 T5 P3 right: F4 F8 C4 T4 P4 T6 |
| Duration: | $\approx 4$ seconds |

Table 2: Sound Examples for Spectral Mapping Sonification of EEG data. The sounds for the conditions pseudo speech and speech are separated by a small gap.

plexity of the sonification. With larger values of $\delta$ the majority of signal energy is cut off and only the spectral peaks contribute to the sound. Correlations between different bands can be perceived as pitch patterns, e.g. one may observe high pitches frequently to follow after some low pitched sounds. As this sonification technique enables to listen to the data at various time scales including real-time, it may even be a useful technique to monitor brain activity in parallel to the stimulus.

Unfortunately, these sonifications cannot distinguish different channels. This limitation could be partially overcome by assigning different timbres to the time-variant oscillators, depending on the channel. However, this would reduce spectral resolution due to the spectral richness of complex timbre.

To summarize, this sonification represents a technique to monitor EEG data spectrally resolved and allows to compare data variations in different channels.

## 4. DISTANCE MATRIX SONIFICATION

Whereas the last sonification was concerned with allowing the user to follow the spectral activation within the brain, this sonification focuses on a less direct and more abstract variable: the synchronization of different brain areas as a function of time. It is an open research question how information is processed in brain in terms of information flow. A working hypothesis is that electrodes having a similar spectral activation profile over time are in a way concerned with similar information processing tasks. Such information can be expressed in form of a time-dependent distance matrix $\mathbf{D}$ with elements

$$D_{ij}[m] = \|\tilde{\mathbf{s}}_i[m] - \tilde{\mathbf{s}}_j[m]\| \tag{4}$$

which contain the Euclidian distance between the normalized spectral vectors of channel $i$ and $j$ in the $m$th window, beginning at sample $C \cdot m$ or at time $t = Cm/\nu_{SR}$. Figure 3 shows some distance matrices for succeeding time frames. Small entries in the distance matrix $\mathbf{D}$ indicate similar activity in these channels. High similarity is usually expected for electrodes with a small topological distance on the scalp. Topological distance between electrodes have been measured by a Polhemus tracker [8]. Thus, for sonification, the topological distance between electrodes is used to drive the pitch of auditory grains which are superimposed into the sound vector at the appropriate onset. The similarity $\exp(-D_{ij}[n])$ is used to drive the level of these grains. Thus loud and high pitched contributions indicate interesting couplings. However, such behavior is even more interesting, if the electrodes carry significant
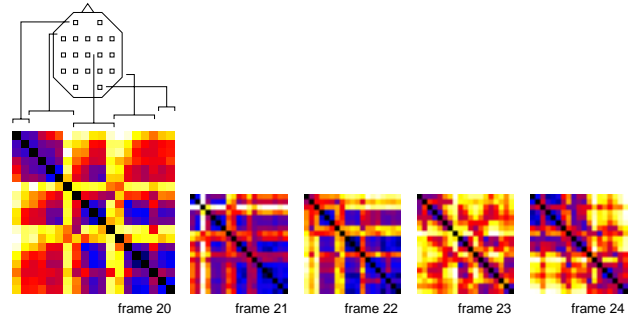


frame 20   frame 21   frame 22   frame 23   frame 24

Figure 3: $19 \times 19$-distance matrix for spectral vectors for 3 succeeding frames. The channels are ordered as depicted from left to right. Small values are represented by dark colors and indicate similar activity between respective channels.

energy. Thus, the product $|\tilde{\mathbf{s}}_i \tilde{\mathbf{s}}_j|$ is used to define the duration of the grains. Hereby correlations between channels having few energy automatically do not dominate the sound as they last much shorter than the terms with higher energy channels. As a final ingredient, sound spatialization is used to give a coarse indication at which electrodes the coupling takes place: if both electrodes are located on one side of the scalp the sound is played on the respective audio channel, couplings between different hemispheres are represented by tones played from the center. Some sound examples are compiled in Table 3. They suggest that more long-range couplings occur in the speech condition, as compared to the pseudospeech condition.

| File/Track: | frequency range: 8-20 Hz |
|---|---|
| | sounds for subjects: S1, S2, S3, S4, S5, S6 |
| Duration: | $\approx 5$ s |

Table 3: Sound Examples for Distance Matrix Sonification. Each example contains first the sonification for the pseudospeech condition, and then after a short noise burst the sonification for the speech condition.

So far, these sonifications allow to inspect the range and strength of couplings between different channels, although it is not possible to infer to the source of the couplings from the sound. In the current examples no information about the stimulus is available. Listening to the sonifications simultaneously with the presented stimulus or a set of auditory markers corresponding to meaningful elements within the stimulus (e.g. tones to mark nones, verbs, negations or phrase ends) could further enrich the sonification.

## 5. DIFFERENTIAL SONIFICATION

The following EEG data sonification allows the comparison of data recorded for one subject under different conditions in order to accelerate the detection of interesting channels and frequency bands along which the conditions may cause systematic differences. In contrast to the previous sonifications, here the time axis is used to distinguish the location of the electrodes, scanning the brain from the frontal side to the occipital electrodes. A basic question while comparing EEG data from different conditions is, which channels have different frequency-specific activations. For

the comparison, for each condition $\alpha$, each channel $i$ and each frequency band $k$, the time sequence of Fourier coefficients $|\tilde{s}_\alpha^i[j,k]|$, $j = 1, \ldots, N_{i,\alpha}$ is used, which is obtained from the short time Fourier transform as described above. The mean

$$\mu_{\alpha,k}^i = \frac{1}{N_{i,\alpha}} \sum_j |\tilde{s}_\alpha^i[j,k]| \tag{5}$$

and the standard deviation

$$\sigma_{\alpha,k}^i = \sqrt{\frac{1}{N_{i,\alpha} - 1} \sum_j (|\tilde{s}_\alpha^i[j,k]| - \mu_{\alpha,k}^i)^2} \tag{6}$$

is computed. Assuming that both sequences are independent samples from the same distribution $p(\cdot)$, the random variable

$$\tilde{t} = \frac{1}{\sigma_{\alpha,\beta,k}^i}(\mu_{\alpha,k}^i - \mu_{\beta,k}^i) \tag{7}$$

with

$$\sigma_{\alpha,\beta,k}^i = \sqrt{K((N_{i,\alpha} - 1)(\sigma_{\alpha,k}^i)^2 + (N_{i,\beta} - 1)(\sigma_{\beta,k}^i)^2)}$$

$$K = \frac{1}{\nu}\left(\frac{1}{N_{i,\alpha}} + \frac{1}{N_{i,\beta}}\right)$$

is student-t distributed with $\nu = N_{i,\alpha} + N_{i,\beta} - 2$ degrees of freedom. With increasing values of $\tilde{t}$, it gets more significant that the means for the condition $\alpha$ and $\beta$ differ. $\tilde{t}$ is thus used within the sonification to decide, if a sonic marker for frequency band $k$ and channel $i$ contributes to the sonification and at what level.

The sonification for a comparison of EEG data for conditions $\alpha, \beta$ consists of a sequence of sonic events whose structure and meaning is given in the following:

- **Time Ordering:** the sonification can be regarded as a scanning from the frontal side to the occipital side. To increase utility of the time axis, electrodes from the left to the right side are separated within each row as shown in Figure 4.

- **Spatialization:** comparison results concerning electrodes from the left (resp. right) side of the brain are presented on the left (resp. right) audio channel.

- **Spectral Mapping:** The frequency band center frequency is a monotonous function of the initial pitch of the sonic marker. Thus changes within the $\beta$-band result in high-pitched events, changes within the $\delta$-band in low-pitched markers. Equal musical intervals (e.g. quint) are used for spectral spacing between neighbored bands.

- **Spectral Motion:** Comparison results indicate either increase or decrease of activation. To monitor these qualitative states, frequency drifts (chirp) within the markers are used. Although this may not be the most intuitive mapping (energy increase would be associated with increase of level), this assignment has a better saliency.

- **Event Level:** Comparison results with $\tilde{t}$ not exceeding a threshold $t_{min}$ are suppressed, allowing to reduce the complexity of the sonifications to significant changes. The level of played events increases with $\tilde{t}$.

- **Marker Sounds:** for sound generation, exponentially decaying sine functions are superimposed. The frequency is driven linearly from its initial to its final value.

- **Acoustic Axis/Labels:** For sonifications longer than one second, an uprising arpeggio is played beforehand to present all center frequencies used for the frequency bands. To facilitate the spatial assignment of perceived events, a marker sound is played on each new row to be started. This is particularly useful in the case that only few markers are played due to a high threshold of $\tilde{t}$.
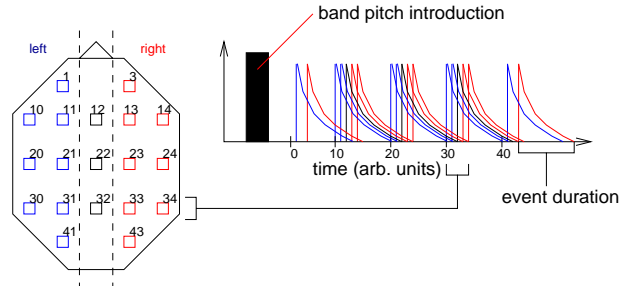


Figure 4: Illustration of temporal and spatial organization of acoustic events in Differential Sonification. The plot shows the amplitude envelope of electrode sound events at a function of time.

Figure 5 shows the STFT of a typical sonification. The up/down-chirp can be seen there. The sound is available at our web site [6]. A set of differential sonifications for 6 subjects and the conditions
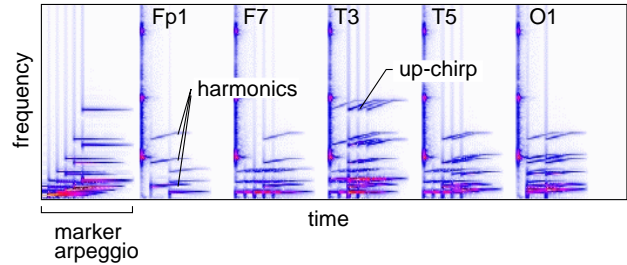


Figure 5: Spectrogram of a Differential Sonifiation for pseudospeech compared to speech. Frequency drifts are seen as spectral motion.

pseudospeech/speech and EEGr/speech are compiled in Table 4. For the untrained listener, it may be an easier start to begin with

| Sound: | pseudospeech vs. speech, 1 sec | S1–S6 |
|---|---|---|
| | same with higher threshold, 1 sec | S1–S6 |
| | speech vs. EEGr, 1 sec | S1–S6 |
| | pseudospeech vs. speech, 4 sec | S1–S6 |
| Duration: | 1 sec (resp. 4 sec) | |

Table 4: Sound Examples for Differential Sonification of EEGr/Speech and pseudospeech/speech

the examples of 4 seconds duration to learn interpreting the sound. However, after some training, shorter sonifications should be preferred as they allow to scan more subjects in shorter time and better keep them in short-term auditory memory as 'auditory gestalts'. The main result from these sonifications is to detect the common pattern, that under the speech condition, more activation is found

mainly in the lower frequency bands ($\alpha_1$, $\alpha_2$ ), mainly in the occipital sector. Furthermore it can be perceived that brain activation during speech perception is also higher throughout the whole brain than under the EEGr condition.

Differential Sonifications are an example for using sound in a more abstract way: here time is used different from its meaning in the data. This sonification shows many ways of further extension, mainly concerning the complexity of the marker events. The presented marker sounds are currently very simple structured. We propose to use timbre, timbre evolution and controls for the amplitude envelopes of the marker sounds to enrich this sonification further.

## 6. CONCLUSION

EEG data are a particularly interesting type of data for the application of sonification since it consists of multiple time series. This kind of multi-channel data contains a lot of noise which complicates automatic pattern detection so that an exploratory analysis can take great profit from the high-developed human auditory skills in signal/noise separation. Sonification can be applied to data analysis for different tasks. For primary data screening, data audification allows to detect outliers and rhythmical and pitched patterns in the raw signals. Spectral Mapping Sonification allows the researcher to bring in his listening skills to investigate frequency-specific patterns of different EEG channels. Besides that, the data are monitored at a high time resolution. Distance Matrix Sonification transforms the data into a sound that allows to detect long-range couplings of brain regions with high temporal resolution. In contrast to visualization techniques which may use grouping of animated markers to represent similarity of electrode signals, the sonifications offer the advantage that temporal patterns in the auditory domain are much better memorized. Finally, the Differential Sonification allows to scan a large database of EEG data recordings in a very condensed way. The trained listener can conclude coarsely which electrodes and what frequency bands were affected by the relevant condition.

Only very few possibilities of sonification for the analysis of EEG data have been addressed. So far none of the presented sonifications made use of the given acoustic stimuli. We propose to add an auditory stream containing specific marker sounds that correspond to the stimuli which were presented to the subjects. Such a simultaneous playback is suspected to allow the listener better to follow the temporal evolution of brain activity with respect to the processing of the stimuli. These extensions are subject of ongoing work and will be presented elsewhere.

## 7. REFERENCES

[1] E. Niedermeyer and F. H. Lopes da Silvia, Eds., *Electroencephalography: Basic principles, clinical applications and related fields*, Lippincott Williams & Wilkins, Philadelphia, 4 edition, 1999.

[2] G. Mayer-Kress, "Sonification of multiple electrode human scalp electroencephalogram," Poster presentation demo at ICAD '94, `http://www.ccsr.uiuc.edu/People/gmk/Projects/EEGSound/`, 1994.

[3] E. Jovanov, D. Starcevic, A. Samardzic, A. Marsh, and T. Obrenovic, "EEG analysis in a telemedical virtual world," *Future Generaion Computer Systems*, , no. 15, pp. 255–263, 1999.

[4] H.M. Müller, S. Weiss, and P. Rapelsberger, "EEG coherence analysis of auditory sentence processing," in *Quantitative and Topological EEG and MEG analysis*, H. Witte, U. Zwiener, B. Schack, and A. Doering, Eds., Jena, 1999, pp. 429–431, Universitätsverlag.

[5] S. Weiss and P. Rapelsberger, "EEG coherence within the 13-18 hz band as a correlate of a distinct lexical organisation of concrete and abstract nouns in humans," *Neuroscience letters*, , no. 209, pp. 17–20, 1996.

[6] T. Hermann, "Sonification for exploratory data analysis – demonstrations and sound examples," `http://www.techfak.uni-bielefeld.de/~thermann/projects/index.html`, 2002.

[7] N. Birbaumer, *Biologische Psychologie*, Springer, 4. edition, 1999.

[8] Polhemus Corporation, "3d motion tracker," `http://www.polhemus.com/home.htm`.