ORCHESTRAL SONIFICATION OF BRAIN SIGNALS AND ITS APPLICATION TO BRAIN-COMPUTER INTERFACES AND PERFORMING ARTS

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ABSTRACT

Electrical brain signals (Electroencephalogram, EEG) as well as other physiological measures can be sonified with a device called POSER, a module of the brain-computer interface 'Thought Translation Device' (TTD). Orchestral sonification allows for presentation of several EEG components simultaneously in real-time, referred to as 'brainmusic'. Here, a number of applications are discussed which were realized. The results of a pilot study are presented in which 12 participants should regulate their mu-rhythm by imagination of hand movements supported by stereo feedback of the mu-rhythm. In the first session already 7/12 participants achieved significant control.

As a basis for developing applications of 'brainmusic', the properties of different spectral components of the EEG are explained and appropriate sonification methods are described.

Using 'brainmusic' for a live interaction with brain signals in terms of moving into the music of one's own brain requires a detailed analysis of possible artefacts in order to understand the limitation of such an approach. The role of movement artefacts and the problem of discriminating the origins of parameters responsible for a certain sound are critically discussed to give a picture of what can be expressed in a modern dance performance demonstrating an interaction with sonified physiological signals.

Finally, some examples for using 'brainmusic' in performing arts are presented, namely a lecture performance, braindance, and a brain meditation concert.

1. INTRODUCTION

At the previous ISON workshop an EEG feedback device (POSER = Parametric Orchestral Sonification of EEG in Real-time) was presented that allows for multi-channel real-time sonification of brain signals. In 2004, Hunt and Hermann [1] mentioned the importance of interactivity in sonification. The

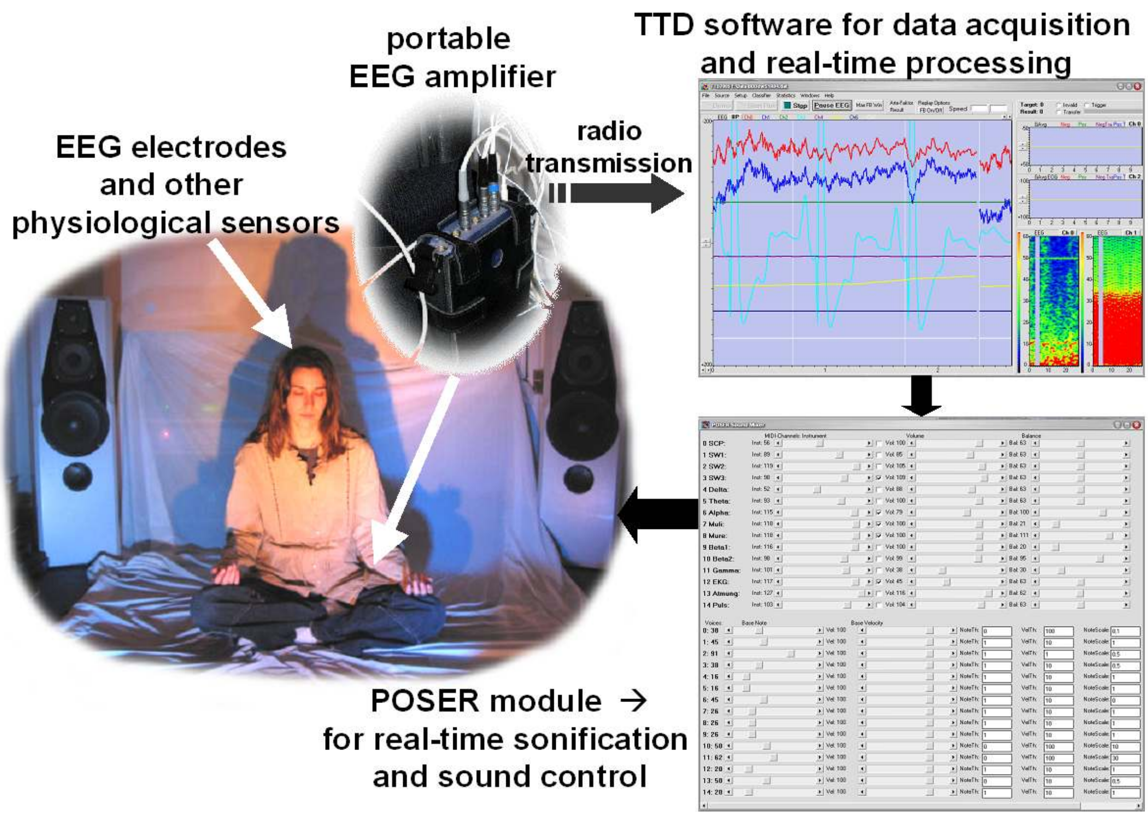

Figure 1: *Feedback setting of an interactive 'brainmusic' concert. The performer wears a portable EEG amplifier that sends the signal wirelessly to the TTD software. The TTD performs real-time filtering and other signal processing and sends the data to the POSER module for sonification. The sonified signals are presented over loudspeakers so that the performer can interact with the sound of its own body.*

POSER system offers one possibility to realize an interactive sonification device and its applications are described here. Its implementation was realized by modification of the brain-computer interface 'Thought-Translation Device'. The system provides simultaneous sonification of various EEG parameters such as slow-wave, spectral power density of different frequency bands, rhythmic properties, etc.. The focus now is on the applications of the device. While, for example Baier et al. [2] focused on a clinical application, i.e. the offline sonification of epileptic activity, the focus here was on the real-time interaction as being important for controlling a brain computer interface and the more playful application of 'brainmusic' in performing arts. In a pilot study with the POSER system, subjects were asked to voluntarily influence specific auditory items of their brain concert by mental strategies while listening. It was shown, that some of the participants could achieve control over certain EEG parameters already in the first session [3].

Results of a pilot study are presented in which twelve participants received feedback of their mu-rhythms. The mu-rhythm is an oscillatory component of the EEG with about 12-15 Hz that can be measured over motor areas of the brain in resting states. Movements or imagination of movements diminish the amplitude of this oscillation in the corresponding area which allows people for operating a brain-computer interface. As a second application of EEG real-time sonification, the system was used for a modern dance performance called 'braindance'. Electrodes were attached to a dancer's head who was carrying a small portable EEG amplifier. Other physiological signals such as the electrocardiogram (ECG) or respiration were additionally acquired. All signals were transmitted wireless to the sonification device which either presented the sounds of single parameters or of the entire physiological concert over speakers to an audience. The dancer could interact with the sounds, empathize with her brain music and express this to an audience by means of body movements. As her emotions, mental activity, and movements have some influence on the signal and therewith the sound as well, a closed feedback loop is created which blurs the boundaries between cause and effect.

Figure 1 illustrates the experimental design of this interactive sonification approach.

2. POSER SONIFICATION DEVICE

The 'Thought Translation Device' (TTD) is used as a core module to realize real-time sonification of physiological measures. the TTD was designed as Brain-Computer Interface (BCI) that allows for feedback of various EEG parameters such as slow cortical potentials (SCP), mu-rhythm activity, or epileptic spikes [4]. SCPs are slow EEG changes below 1 Hz correlated with mental preparation and relaxation. Many people can learn to voluntarily regulate their SCPs in a feedback training. A classifier can be used to identify brain states and use them to drive applications such as a letter selection module or a brain-controllable web-browser [5]. Completely paralyzed patients were able to communicate with the TTD using their brain responses only [6].

The need for an auditorily driven BCI led to the development of auditory feedback paradigms for brain-computer communication [7];[8]. The fact that we are able to discriminate between multiple acoustic sources and react in specific ways, belongs to the basic skills of the human auditory system. It is not only a useful ability which is used for orientation in daily life, above all it is a source of enjoyment and pleasure as music is based on this property of audition. The question is, why not use these skills for learning something about our inner processes or even interacting with them? This is the idea of the development of a device that allows for 'Parametric Orchestral Sonification of EEG in Real-time' (POSER). POSER is presenting a variety of EEG components at the same time over the acoustic channel instantaneously as a live feedback signal to the user or an audience. A sub-module was programmed that interfaces the computers' MIDI system in a way that pre-processed signals serve as the sound parameters. Depending on the type of signal processing EEG or other physiological measures select notes, velocity, and rhythm. Up to 16 different instruments can be played simultaneously; each of them controlled by any physiological parameter. In the screen shot of the sound control window of the POSER module in Figure one can see that the various sound parameters can be chosen for each MIDI channel and each sonified parameter separately. Additionally, a script language has been developed that allows for altering sound parameters more flexibly which is useful in performances.

Sonification of EEG parameters below 20 Hz is most suitably carried out by transforming the continuous signal into a sequence of discrete events. The approach of Baier and Hermann is also based on this principle [9]. The following method is used in the POSER system, now referred to as wave-beat modulation (WBM) [3]. After the EEG was filtered to its standard frequency bands the wave cycles can be used for triggering sounds. The pitch is determined by the frequency of the wave maxima while the velocity reflects the amplitude of a wave cycle. A baseline note and velocity as well as a scaling factor are required for appropriate modulation of note and velocity. A logarithmic (logarithmus dualis) scaling of the trigger frequency multiplied by 12 (12 semitones per octave) is employed to maintain frequency relationships of the signal. Rhythms (temporal relationships of signals) remain audible as the threshold for a touch is exceeded only at wave maxima. For an orchestral sonification each instrument of the MIDI sound system can be assigned to specific parameters extracted from the EEG.

3. CONTROLLING SONIFIED MU-RHYTHMS

Sonification of an EEG-rhythm using the POSER (Parametric Orchestral Sonification of EEG in Real-Time) module of the TTD as reported in [3] allows for interaction with a variety of immediately available sonified EEG components. In a study with 12 healthy subjects mu-rhythm control with lateralized feedback of the sonified rhythm was investigated. The mu-rhythm was picked up at the electrode positions C3 and C4 (about 7 cm to the left and right from vertex towards the ears) referenced to the mastoids (electrodes fixed at the bone behind the ears) and was band-pass filtered in the range from 8 to 15 Hz. The rhythmic activity was sonified and fed back to the subjects with stereo speakers. In the orchestral setting for the left mu-rhythm instrument no. 33 (acoustic bass) in the General MIDI table was used as instrument with the baseline note no. 52 (E - Octave: 3). The sonification of the left mu-rhythm was audible over the left speaker only. The same MIDI instrument was assigned to the right mu-rhythm with baseline note no. 59 (B - Octave: 3). The sound of the right mu-rhythm was played via the right speaker. Subjects were instructed to imagine the movement of their left or right arm and thereby control the stereo balance of the sounds audible over the speakers. Instructions indicating whether the movement of the left or the right arm was to be imagined were presented visually and auditorily. On the monitor two green boxes were displayed, one on the left and one on the right side of the screen. After one second an auditory instruction lasting for one second was given by a voice saying ‘left’ or ‘right’ and at the same time an arrow points to the green box on the corresponding side which then changed its color to red. During the next 9.5 seconds the subject's task was to concentrate on the imagery of the movement of the indicated arm. Imagining a left hand movement should lead to a desynchronization of the rhythm at the contralateral side. Therefore, only the rhythm on the imagined side should remain audible. The volumes of the mu-rhythms informed about the lateralization of the mu-rhythm, i.e., it indicated how well their imagination of the hand movement was represented in the EEG. At the end of a trial all boxes turn green until the next trial starts. The subjects performed 210 trials in one session comprising 3 runs of 70 trials each. The regulation of the mu-activity in this initial training session was investigated. The average power spectrum density (PSD) in the range from 8-15Hz during the feedback interval was calculated. The PSD difference between the right (C4) and left (C3) mu-rhythm served as a measure for the statistical analysis and off-line classification of the mu-rhythm lateralization. For offline classification, a threshold in the PSD difference was determined which separated the two tasks best.

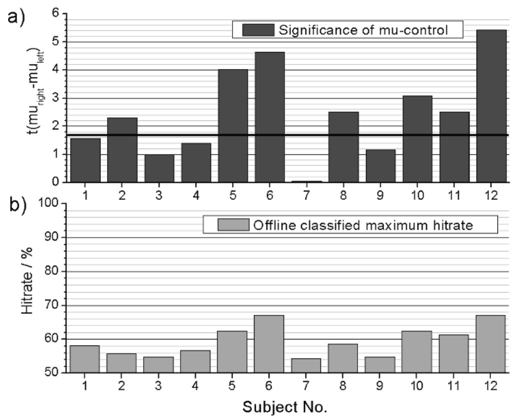

Figure 2: *a) Initial success in mu-rhythm control mediated by real-time feedback of the sonified mu-rhythm in a stereo reproduction. A t-test was performed to test for the difference between left and right mu-rhythm. The horizontal line at 1.65 indicates the 5% significance level. Seven out of the 12 healthy subjects achieved significant control during the first 210 trials. b) Five participants achieved more than 60% correct responses in an off-line classification of the sonified mu-rhythm lateralization.*

The hit rates obtained with this process are shown in Figure 2 b. Figure 2 a illustrates the results of a t-test statistic for each subject. 7/12 subjects achieved significant classification already in the first 210 trials and 5/10 exceeded a correct response rate of 60%. The response accuracy is expected to be increased with further training, but also by determining a subject specific optimal frequency band, and selecting more appropriate electrode positions by multi-channel recording. A comparison between visual and auditory sonified mu-rhythm control is missing and should be investigated in a future study.

4. MEASURES FOR PERFORMANCES

In this paragraph a description is given of how one could use various physiological measures (i.e., EEG and peripheral measures) for an aesthetically pleasing and easy to understand representation of a signal in order to allow an audience to empathize with it. The limitations and the influence of artifacts are discussed.

4.1. EEG Parameters

The *slow cortical potentials* (SCP) below 1 Hz are continuous amplitude changes without showing clear regularities. As they are not perceived as rhythm a conversion into single beats is less appropriate. It is suggested to transform the slow changes into a smooth chain of low frequency sounds changing their pitch according to the slow wave amplitude.

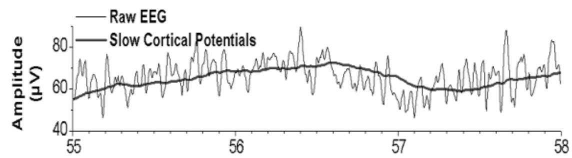

Figure 3. *The slow waves are sonified by playing the trace of the low-pass filtered EEG.*

The *delta* (1-4 Hz) and *theta* (4-8 Hz) waves show more or less oscillatory behavior. Strong oscillatory Delta waves are normally associated with deep sleep states. But even in normal wake states, some delta activity is normally present as illustrated in the spectral graph in Figure 4. However, the delta activity of waking states is much less intense and mostly of non-oscillatory nature. Its spontaneous fluctuations can be seen as noise with a broadband spectrum. The same is valid for the theta band activity. Strong oscillatory theta is measured in states of drowsiness and some meditative states. An appropriate sonification according to the WBM principle explained in chapter 2 will lead to a pulsation or sound beats of a more or less regular frequency of 4 to 8 Hz. Choosing a modulation of pitch as proportional to the frequency of wave cycles, it could be possible to recognize harmonic structures. Most probably however, they are smeared by the uncertainty of the poor frequency resolution of spontaneous events.

Alpha band activity mostly is a strong sinusoidal wave. It reflects resting states by showing synchronized activity of large assemblies of neuronal areas. The sinusoidal waveform can already be seen in the unfiltered signal as an oscillation within a narrow frequency range around 10 Hz. The distinct frequency of alpha oscillations therefore sound as monotonous vibrations. A frequency modulation can be used to sonify the small frequency changes in terms of changes in pitch.

The *beta band* (12-30 Hz) reaches the crossover from the frequency range in which waves are perceived as rhythm and vibration in which single cycles can be distinguished by our auditory system and those frequencies higher than 15 to 20 Hz which are perceived as a continuous tone. Mainly beta band activity consists of broad band noise and does not show single frequency peaks. Sometimes a beta peak with a specific frequency can be measured over the sensorimotor cortex. For sonification of the beta band signal, the WBM principle is therefore not an appropriate method as it would lead to a conversion of a broad band signal into time series of chaotic events. It is suggested to choose a method which maintain the noisy structure of beta activity. Upconversion of the band power information into higher frequencies would be one option. To be consistent with the use of the MIDI device and the abilities of the POSER system led to another method. MIDI provides more or less noisy instruments. They are used to play the beta band by modulating their volume with the ongoing spectral power density changes of the beta band activity.

The same is valid for the *gamma band* (>30 Hz). However, normal gamma activity shows very low power and reliable information is therefore not very well retrieved especially if the person is not in an absolutely relaxed and resting position. The typical 40 Hz gamma oscillations appear in a narrow frequency band and can be measured in some people quite well. They are associated with like recognition of patterns and structures.

Two sound examples can be downloaded from the web as examples for sonification of each rhythm separately and all rhythms played together [SingleRhythms.mp3; AllRhythms.mp3].

4.2. Peripheral Measures

Eye-blink sonification: For a sonification of eye blinks it is necessary to attach electrodes above and below, or left and right to the eyes for recording the electrooculogram (vertical or horizontal EOG). Eye blinks produce peaks with amplitudes of a several hundred micro-Volts and a duration of several hundred milliseconds. These peaks are suited for triggering the touch of an instrument.

Eye movements lead to positive or negative amplitude shifts. Using the first derivative to drive a sound is my suggestion for sonifying eye movements.

Pulse sonification: The pulse or heart beat can either be measured optically with a clip on the finger or earlobe or electrically with ECG electrodes. the optical signal leads to an almost sine-wave shaped signal while the ECG entails a more complex signal. For extracting the heart rate information from the ECG the R-peaks are used to trigger a counter. Triggering sound events with hearts beats provides a rhythmic basis for a physiological concert.

ECG sonification: An ECG wave usually consists of 3 characteristic peaks during the period of one beat: the so-called R-peak as a high amplitude spike and two smaller humps. Applying the WBM method in a way that all three peaks serve as triggers for a sound a quite complex and interesting sonification arises. All three beats have different volume and pitch which is determined by the time to the previous peak. Interestingly, small variations in the regularity and arrhythmia are heard easily. Three sound files can be heard on the web illustrating ECG sonification [ECGsound1.mp3; ECGsound2.mp3; ECGsound3.mp3].

Skin conductance response (SCR): SCR measurements also require a motionless resting position. On emotional affects, the response is a slowly rising curve with a latency of about 1 s and a duration of several seconds. Similarly to the sonification of SCPs it makes sense to use the first derivative as a pitch controlling parameter.

4.3. Artifacts

Artifacts caused by the eyes: Eye blinks and eye movements are the most critical artifacts in scientific EEG measurements as the eye bulb is a dipole which causes amplitude shifts when turning. In many studies the EEG is corrected for eye blinks or epochs with strong eye movements or blinks are removed offline. Such artifact handling requires additional recording of eye signals (Electrooculogram, EOG). Eye blinks in EEG channels can be removed online with the TTD system. However, EOG signals can be purposefully utilized for manipulating sound parameters with a much higher degree of control than any EEG parameter.

EMG artifacts: The EMG which is measured at an EEG electrode on the scalp is treated as an artifact. Static muscle tension causes high frequency (>10 Hz) EMG (electromyogram) activity. EMG artifacts of turned head originate at the neck muscles and intersperse to the mastoidal reference electrodes as it can be seen in Figure 4. The EMG activity from jaw muscles are also sometimes strong enough to significantly distort the EEG signal measured at cortical electrode positions.

Movement artifacts: Movements of body parts especially in the face or near the head also cause low frequency artifacts. This is illustrated in the last graph of Figure 4b) as well as in the corresponding spectral graph. The difference between the spectrum of the 'turning the head' condition and the ballet dancing expresses the additional low frequency (<10 Hz) artifacts when extensive movements are carried out.

Non-physiological artifacts are possible signal components which are caused by either external noise being picked up by the amplifier or signals which are produced inside the electrodes, wires, or the amplifier. A 50 Hz influence caused by high electrode/skin impedances is normally no problem as the skin can be prepared. Artifact free slow wave recordings require sintered Ag/AgCl electrodes in order to avoid potential drifts caused by polarizations at the electrode material. In non-shielded electrode wires shaking can easily induce artifact currents and high slow wave potential shifts. As many modern EEG systems such as the one we are using for performances are equipped with actively shielded electrodes those artifacts created by shaking the wires during movements remain below the visibility threshold as demonstrated in Figure 4. Only movements of the skin at the position of an electrode will cause some low frequency artifacts.

Artifacts as an artistic element: Normally, the dancer can hardly influence brain patterns in an easy to perceive way. However, the voluntary production of artifacts can be utilized for creating special effects. This can be done in a quite obvious way allowing the audience to follow acoustically movements or muscle tension. For example, the EMG signals created by clenching the teeth or turning the head can be used for modulating sonified beta and gamma band activity. Purposeful sonification of EMG is also utilized by Pauletto and Hunt [10].

Sonification of eye-movements or eye-blinks can also be used as an artistic tool to express auditorily the action of the eyes. For example, Indian temple dancers use extensively eye gazes as an artistic element which then could be used for composing sounds with the dance in a live situation.

Also the control of sound parameters with the low frequency signals of body movements offers the dancer to interactively tune into the sound of his/her movements.

5. APPLICATIONS

In the following, some contexts or projects are mentioned in which the POSER device was used as a tool for illustrative presentations.

Demonstrations: EEG signals as well as other physiological signals are time series signals and their parameters vary in a time range that can be easily followed by our audition – either in form of a slope of a tone, a rhythm, or a sound. It is therefore an appropriate tool for demonstrating the properties of specific

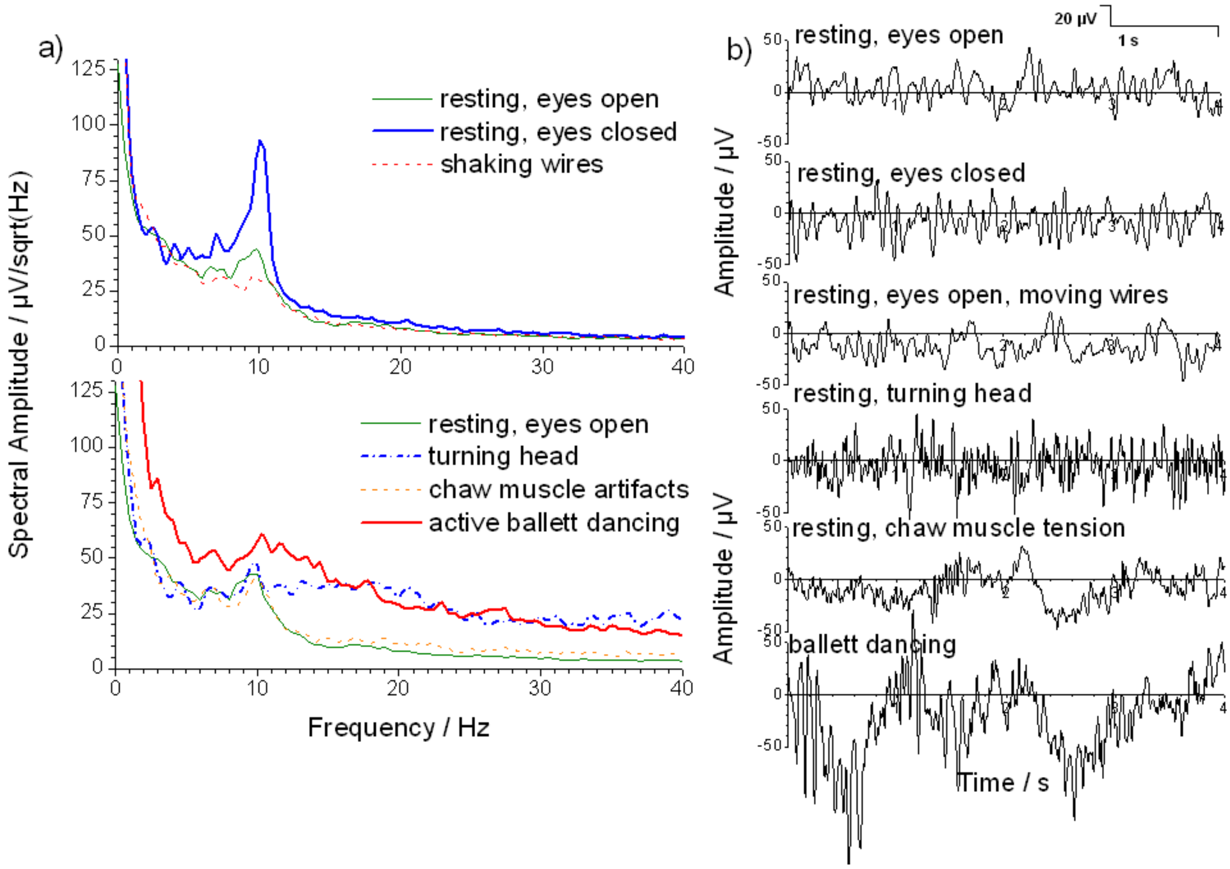

Figure 4. *Quantitative investigation of EEG waveforms and spectra during performance tasks. The most easy to demonstrate EEG change is the alpha rhythm with a frequency of about 10 Hz which can be doubled in a resting position by closing the eyes. Artifacts created by shaking the wires remain irrelevant as actively shielded electrode wires were used. Slow movements such as turning the head create higher frequency EMG signals from muscle tensions which are superpositioned to the EEG signals in the beta and gamma band. Full body movements in a ballet dancing style cause additional low frequency movement artifacts which are also superpositioned with the normal EEG.*

EEG components to an audience which is not used to read scientific graphs. A vivid demonstration of brain processes can be given in form of a lecture performance as it can be seen in Figure 5.

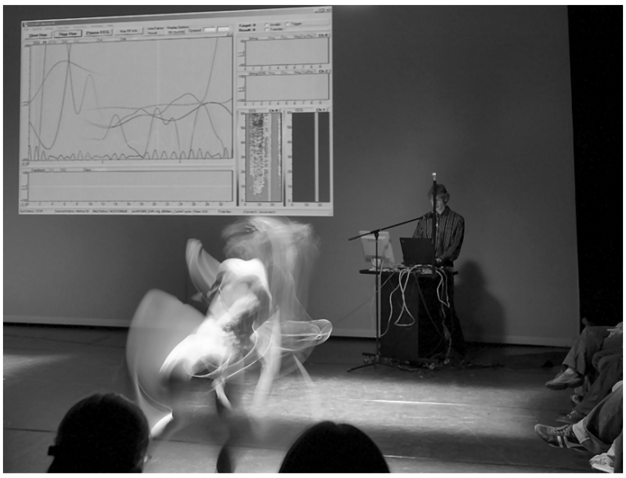

Figure 5. *A lecture performance presenting live sonified brainwaves from a dancer who is interacting with them in a modern dance performance is an illustrative example of linking scientific measurement methods with artistic expression.*

Interactive dance performance: The real-time interaction of a dancer with his/her own sonified brain signals is an aesthetic way to show the inner life of brain signals and express the interaction of body and mind in an act of modern dance. A 'braindance' duo was presented in 2004 at the International Media Art Award festival in Baden Baden, Germany, in which the EEG electrodes were attached to a female dancer representing the mind and the male dancer represented the body by wearing the ECG electrodes for sonification of the heart beat and a respiration sensor for sonification of the breath. The interplay between the mind and the body was presented in a choreographed act showing how the body carries the mind, how the mind can dominate the body and how both depend on each other for staying alive. Figure 6 shows a scene.

Meditative brain concerts: One of the first interactive EEG compositions were presented by Alvin Lucier in 1965. He used bursts of alpha waves from a performers head while sitting in a meditative, non-visual brain state to vibrate percussion instruments distributed around the performance space. Later, David Rosenboom presented interactive music systems controlled by EEG and other physiological signals [11; 12]. Another artist working with sounds created in real-time from breaths, heartbeats and brainwaves while sitting quietly is Adam Overton. For his piece 'Sitting. Breathing. Beating. [Not]

Thinking.' he was using the SuperCollider sound software connected with an EEG/ECG device [13; 14].

Figure 6. *Braindance duo: the female dancer is wearing the EEG electrodes while the heart beat and respiration is picked up from the male dancer. In a choreographed act they present the interplay between the mind and the body.*

With the POSER system a meditative brain concert entitled 'Listening to the invisible 'now'' was presented at the Brainspotting Festival in Amsterdam. in 2006. The real-time concert was associated with a message. Thoughts and states of consciousness are a hidden privacy for each of us as long as we do not share them by muscular expressions. Presenting 'brainmusic' is an alternative channel for sharing correlates of this privacy. Another key feature of a 'brainmusic' concert is that consciousness and awareness is only possible in the present. Meditation is a tool to lead us into the reality of the "now". Here we try to bring the audience into this presence by the presentation of the ongoing inner processes which are related to our consciousness to the outside in the form of sound and rhythm. Using real-time sonification of EEG, a spontaneous concert accompanies a meditator live on stage leading the audience into moments of presence which are the source of time.

6. CONCLUSIONS

Some examples were presented how real-time sonification of EEG can be a useful tool for neurofeedback applications. The field of brain-computer interfaces could profit by a sonified feedback as shown in a pilot study. Feedback of the mu-rhythm for example can be given in a more authentic way as with most other methods. However, whether it is superior to conventional feedback methods (visual or other auditory) still is subject to further investigations.

Experiences with public presentations of sonified EEG in form of lecture presentations or dance performances show that this is an appealing way for introducing an audience to the nature of brain signals. However, as especially in movement situations like in a 'braindance' show artifacts might be involved it should be mentioned that we abandon the claim of presenting pure EEG. Moreover, muscular activities can be demonstrated in sound as well or even can be used as an additional artistic element. In this article, an overview over the major characteristics of EEG, other peripheral measures, and artifacts was given and its possible influence and use for sonification was discussed.

Finally, one should mention that the suggested sonification approaches can be realized with other than the used software as well, e.g., the one from the SonEnvir project [15]. Controlling parameters of external sound synthesis software with the TTD instead of using a MIDI interface could be a next step in this development.

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