POSER: Parametric Orchestral Sonification of EEG in Real-Time for the Self-Regulation of Brain States

Thilo Hinterberger and Gerold Baier

***Abstract*— We introduce a device for the parametric sonification of electroencephalographic (EEG) data. Implemented in the Thought-Translation-Device TTD (a brain-computer interface designed for the communication with completely paralyzed patients), the device allows auditory feedback of multiple EEG characteristics in real time. In particular, each of 6 frequency bands is assigned an instrument of a MIDI device. The time-dependent parameters extracted from each frequency band modulate the timing, pitch and volume of the instrument. In a pilot study we tested the ability of subjects to perform a simple discrimination task using this parametric sonification in real time.**

***Index Terms*— Brain-computer interface (BCI); feedback; electroencephalogram (EEG); parametric sonification.**

I. Introduction

To be able to interact with brain signals using a Brain-Computer Interface (BCI), it is required to achieve control over some parameter of cerebral activity. It was shown that self-regulation of electroencephalogram (EEG) can be used as a channel for information transfer out of the brain [1]. In particular, slow cortical potentials (SCP) can be self-regulated in an SCP feedback paradigm using the Thought-Translation-Device (TTD) [1]; [2]; [3]. The TTD was the first BCI that enabled completely paralyzed patients to generate written messages with their brain activity. Sterman [4] reported the ability of humans to voluntarily control the sensory motor rhythm (μ-rhythm) which desynchronizes when imagining a hand movement. Wolpaw et al. [5] and Pfurtscheller et al. [6] developed BCIs with μ-rhythm control for verbal communication and robot control. All studies mentioned use visual feedback training. Recently Hinterberger et al. [7] presented a comparative study of visual and simple auditory feedback for learning of SCP self-regulation. It was found that simple pitch assignment based on instantaneous signal amplitude did not help to improve SCP classification results of subjects. In addition, combined visual and auditory feedback gave results that were less significant than those with either visual or auditory feedback. We therefore decided to develop a more sophisticated device for auditory feedback. The result, parametric orchestral sonification of EEG in real time (POSER), taps into the capability of the human auditory system to deal with complex sounds.

The paper starts with a brief review of scientific data sonification and its application to the analysis of human EEG, then describes the design and features of the feedback device, and finally presents the results of a classification pilot study.

II. EEG Sonification

Sonification is the generation of artificial sounds using control by data or by parameters extracted from data. A simple example is the "beeping" that indicates individual heart beats during surgery to monitor the stability of a patient's condition. Another example is the pitch of beeps or an instrument in a previous TTD version that encodes the amplitude of a brain potential [7]. Useful as these sonifications are, they represent the most primitive level of sonification, namely, the mapping of only one parameter into the domain of aural perception. This is in sharp contrast to the widespread use of visualization in science which is becoming increasingly more complex as tools like gray-shading, pseudo-coloring, shadowing and animation are available. Given that contrast one might be tempted to ask: why use sonification at all? We believe that human aural processing can deal with much higher complexities than those used for scientific purposes so far. The ability to distinguish between several simultaneous voices or instruments even in a noisy environment provides a particularly good reason to use advanced sonification for learning to deal with multi-parametric data sets such as human EEG.

A milestone in the short history of scientific data sonification was the first International Conference on Auditory Display in October 1992 in Santa Fe, New Mexico. The conference proceedings volume provides an overview of sonification attempts prior to that date and a state-of-the-art summary of the field [8]. In that book, two points of importance for the present work are discussed explicitly. One,

Manuscript received November, 2003. This work was supported by the Deutsche Forschungsgesellschaft (DFG) within the SFB 550 (B5) and the National Institute of Health (NIH).

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auditory display uses artificially generated sounds. Therefore, all sound parameters are under the control of the human “sonifier”. This allows the exploration of multiple parameter mappings, i.e., independent control of pitch, duration, volume, etc. by more than one data parameter [9]. And two, a comparative study showed that human performance depending on multivariate information (simultaneous input from various different sources) was significantly better with an auditory display as compared to a visual display or a mixed visual and auditory display [10]. The authors hypothesized that the auditory advantage may point at “the inherent ability of the auditory system to process multiple auditory “streams” in parallel”, in contrast to the visual system’s serial processing of multiple objects. Two previous attempts to sonify human EEG have tried to take this into account [11]; [12]. However, both were done off-line and have not been implemented for real-time monitoring. Here, we present for the first time a multi-parametric auditory display for real-time application to multivariate EEG data.

EEG is mostly recorded from multiple electrodes and is thus multivariate and complex (each time series typically has a broad-band Fourier spectrum with significant powers between 0.1 and 60 Hz). As such it is a good candidate for multi-parametric data sonification. Electroencephalography has introduced the division of the mentioned frequency range into 6 frequency bands denoted SCP, delta, theta, alpha, beta and gamma band, respectively. With some exceptions the neurophysiologic origin of oscillatory activity within these bands is not known in detail. Among the mechanisms that could be derived from animal experiments are: spindle oscillations in the alpha band are generated in the thalamus; SCPs are elaborated in the neocortex; the delta band comprises different rhythms with different mechanisms in the thalamus and neocortex; theta rhythms can be traced to activity in the hippocampus; and the gamma band is activated by arousal and focused attention [13]. This explains that different mental activities are reflected in the activity of different frequency bands. If one tries to relate changes in a given signal with specific mental activity, it is thus advisable to divide the information from each electrode accordingly. This forms the basis of our approach.

III. METHOD

A. The TTD Framework

The TTD is a powerful framework that allows to create new real-time feedback applications utilizing a variety of signal filters and feedback modules that can be added flexibly [2]; [14]. This is necessary for the development of BCIs in general but provides a special advantage for an application such as POSER. The TTD was programmed taking into account the BCI2000 standard [15]. This standard defines an EEG data file format, a unified parameter handling, suggests a system for circulating status information, and gives a class structure for programming filter modules. The TTD additionally contains an engine that allows a dynamic arrangement and wiring of various filters and modules. This allows implementation of a large variety of experimental paradigms. Finally, the modules for statistical data analysis make the TTD a complete scientific program.

B. EEG Data Acquisition

The TTD can be interfaced by various EEG amplifier systems such as the BrainAmp (MES GmbH, Munich), EMR 16/32 (Schwarzer, Munich), ProComp+ (Brainproducts, Inc.). Amplifiers with analogue output such as the EEG8 (Contact Precision Instruments, Inc.) or gSamp (gtec, Austria) are connected to an A/D converter (DAS series, Measurement Computing, Inc.) connected to the computer of the TTD. EEG is sampled at a rate of 256 per second in an amplitude range of +/-1mV and a resolution of 16 bits. The pilot study was carried out with the ProComp+ system. The raw EEG signal is stored to disk and complemented with status information such as a code for the feedback task and other events during a trial.

C. Data Processing

Data processing is performed at 256 Samples/s while sonification is paced at a rate of 127 per second providing a sufficient update rate and timing resolution. A 1.6 GHz Pentium IV machine running under MS Windows XP showed excellent real-time behavior.

Preprocessing: After calibration of the EEG-signal into µV the spatial filter offers the user to arrange the EEG-channels by a linear combination of incoming channels. In the standard setting three channels of EEG are used: Cz-mastoids, C3-mastoids, C4-mastoids. A rough correction of eye movement artifacts is realized by subtraction of a fixed factorized amount of the vertical Electrooculogram (vEOG) (the factor is about 0.12).

Band pass filtering: The EEG is then band pass filtered into various frequency bands. An FIR (finite impulse response) filter with either 127 or 63 coefficients is used. A moving average of a window of 127 coefficients results in the slow-wave activity (SCP) from 0 to 1 Hz. The next five frequency bands comprise 1 to 3 Hz (delta band), 3 to 7 Hz (theta band), 7 to 12 Hz (alpha band), 12 to 30 Hz (beta band), and 30 to 40 Hz (gamma band). While the four bands up to 12 Hz use 127 filter coefficients, the beta and gamma bands are filtered with 63 coefficients to achieve faster response times.

Extrema detection: Characteristic rhythms of the EEG in the frequency range below 12 Hz are sonified by triggering the touches of a note at the maxima of a wave. For this purpose, maxima are detected in the filtered signals of the first three frequency bands. In addition, the potential differences between subsequent extrema (maxima minus previous minima or minima minus previous maxima) are calculated. The three output signals of this filter carry the potential differences together with the times where the extrema were detected, otherwise they are zero.

Extrema frequency: The inverse time difference between consecutive maxima of a band pass filtered signal serves to estimate the “instantaneous” frequency of a signal.

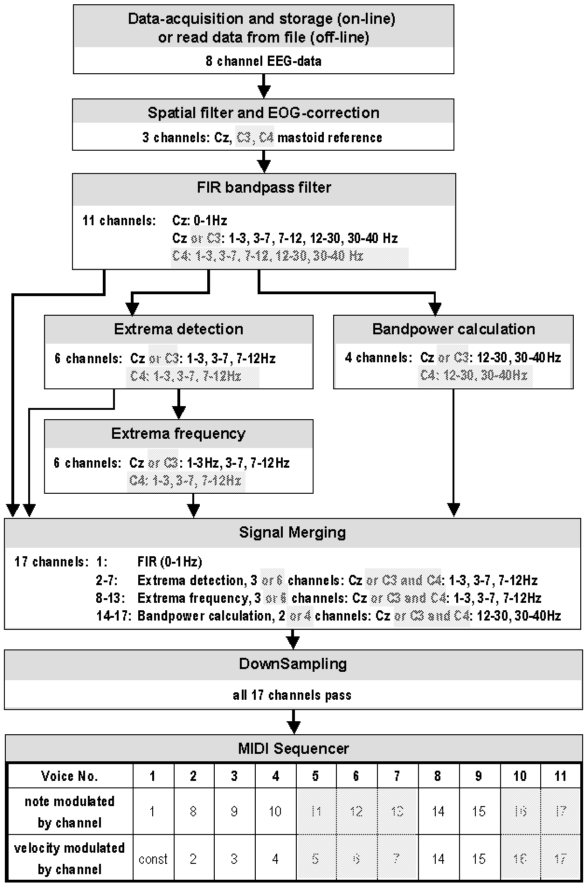


Fig. 1. Signal flow chart of filter modules and channel assignment. In the basic setting, only one EEG channel is used. The gray shaded text shows the optional extension to a bi-hemispheric setup for feedback of the central, left and right hemisphere. Spatial filtering gives a bipolar selection of incoming EEG signals and additionally allows for linear correction of eye-movement artifacts. An FIR band pass filters the signals. The basic rhythms (delta, theta, and alpha) are fed into the extrema detector which exports peaks at the extrema to provide the rhythm with a precision of 1/256 second. Subsequent conversion of peak-to-peak times into a frequency allows to modulate the pitch of an instrument. For frequencies above12 Hz the band power is calculated as the feedback parameter. The “Signal Merging” module merges the different outputs of the previous filters into one signal which, after down-sampling to 127 Hz, is transferred to the MIDI-sequencer. The parameters indexed by the channel numbers can be used for modulation of the note or the velocity of a MIDI voice.

Down sampling: To lower the update rate of the sounds to half the sampling rate, all output signals are down-sampled.

Calculation of band power: As 15 Hz is about the maximum frequency at which two consecutive events can be resolved as distinct by the human ear, the touch triggering of sounds is not appropriate for the beta and gamma band. In these frequency bands we chose the “instantaneous” band power as a representative measure of activity. The corresponding outputs of the FIR-filter are therefore squared and low-pass filtered to obtain the progressional band power.

FFT and predominant frequency search: As an alternative to the band power, the dominant frequency in the beta or gamma band (and its amplitude) could serve as an indicative measure. However, as these higher frequencies are often of low amplitude, it would be necessary to multiply the spectral amplitudes with a frequency dependent value or normalize each spectral amplitude to its standard deviation. This was not pursued further.

Figure 1 illustrates the signal flow and the combination of filters. Figure 2 demonstrates the process of filtering and parameter extraction.

D. *Orchestral Sonification*

The parameters extracted from the EEG are assigned to voices of a MIDI device. A voice, in turn, is assigned to a MIDI channel. The MIDI device of a common PC soundcard provides 16 MIDI channels. Each channel is defined by three parameters for an instrument, its volume and balance. Thereby, each instrument is positioned in aural space. Other specific parameters of a voice are the note (pitch) and its velocity. An EEG parameter can therefore modulate either pitch or velocity, or both pitch and velocity. The EEG parameters carry signal amplitudes with a certain amplitude range. Appropriate modulation of note and/or velocity additionally requires the definition of a baseline note (resp. velocity) and a scaling factor. A threshold parameter suppresses continuous touching.

Parameters were assigned to voices as follows (see Fig. 1, bottom):

Voice 1 plays the SCP continuously in a low register with a constant velocity. In this case the SCP amplitude modulates the pitch of a given instrument in the MIDI table. Voices 2 to 7 represent the delta, theta and alpha band of the left and right hemisphere. Here, the output of the extrema frequency filter modulates the note while the amplitudes of the wave maxima modulate the velocity. A logarithmic (logarithmus dualis) scaling of the extrema frequency multiplied by 12 (12 semitones per octave) maintains frequency relationships of the signal. In addition, as the threshold is exceeded only at wave maxima, temporal relationships (rhythms) also can be

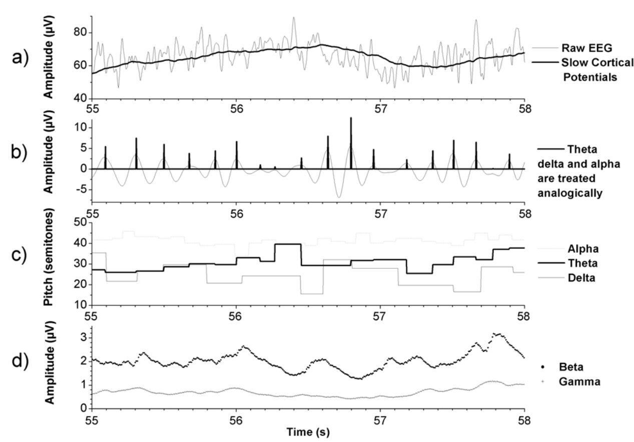


Fig. 2. The extraction of the parameters from an exemplary EEG-trace is illustrated. A) shows the raw EEG and the trace of the slow cortical potentials. B) The theta wave is displayed with the corresponding spikes at the extrema that trigger the touch of the instrument. This reflects the rhythmic properties of the EEG. The spike amplitudes represent the differences between the maxima and the previous minima. The delta and alpha band is treated analogically. C) The pitch is calculated from the elapsed time between two spikes for the delta, theta and alpha frequency bands. D) For the higher beta and gamma frequencies the band-power serves as parameter modulating the pitch and velocity of the corresponding instrument.

TABLE I
SIGNIFICANCE VALUES OF TASK SPECIFIC EEG CHANGES

Parameter	P1 m	P2 m	P3 f	P4 f	P5 f	P6 m	P7 f	P8 f	P9 m	P10 f
SCP	-0,96	0,44	0,38	0,36	-1,37	0,03	0,15	1,22	-1,39	0,18
Delta *p*	**2,26**	0,16	**1,85**	**2,09**	**9,21**	0,56	0,26	0,66	-1,19	**-3,33**
Theta *p*	1,02	-1,54	**-3,07**	**1,91**	**5,15**	0,35	-0,60	0,91	-0,79	-1,16
Alpha *p*	-1,40	0,64	**-3,78**	1,44	**-1,79**	**1,76**	**1,88**	**5,41**	**2,52**	**-2,69**
Delta *f*	0,06	0,16	-1,48	-1,14	**-2,59**	-0,66	-0,16	-0,22	0,90	1,35
Theta *f*	-0,76	0,18	-0,31	-0,39	-0,72	0,22	**-1,94**	0,14	1,27	-0,34
Alpha *f*	-0,18	0,52	**1,72**	0,87	-1,04	-0,65	**2,55**	1,60	0,02	-0,07
Beta *p*	-1,49	-0,71	***-5,98***	***2,96***	**2,73**	0,91	**2,17**	1,32	**3,44**	***-4,71***
Gamma *p*	***-1,88***	**-3,72**	***-4,08***	***3,06***	0,33	-0,05	0,16	**-3,81**	**-5,54**	***-2,50***
r(Beta-Gamma)	***0,51***	0,42	***0,63***	***0,92***	**0,58**	**0,68**	0,31	0,15	0,29	***0,56***

Task specific EEG variations in ten (6 female, 4 male) participants. The values represent the significance (t-values) of the difference between the two tasks for each sonification parameter. The frequency band analysis marked with the italic addition *p* consisted of band power amplitudes, the addition *f* indicated the analysis of the pitch of the rhythm . T-test was performed on the average amplitudes in the interval 2.0 - 8.5 s within a trial. Each participant completed 200 to 250 trials. Significant differentiations are emphasized in bold face. The italic and bold numbers point to significances possibly caused by artifacts such as muscle tension. The gray shaded fields thus show reliable significances.

perceived. A delay of about 125 ms due to the digital band pass filtering is presently unavoidable.

Continuous sounds are used in voices 8-11 for the beta and the gamma band. These are modulated in pitch by the spectral power of the frequency band. A direct conversion of frequency-to-frequency as applied to the slower rhythms is not appropriate here, as both bands often contain mere broadband noise.

E. *Sound Presentation*

Two different setups are implemented: A *basic setting* which only requires one EEG channel, and a *bi-hemispheric setting* with three locations (underlaid in gray in Fig. 1). Both settings profit from a stereo distribution of the instruments. In the basic setting, the instruments for SCP and delta are centered; theta is positioned half left; alpha half right; beta extreme left; and gamma extreme right. In the bi-hemispheric setting the instruments representing left hemispherical EEG (C3) are arranged to the left side of the stereo hemisphere: the right hemisphere is arranged to the right side; and the SCPs are centered. In both settings a high quality stereo sound reproduction is crucial to achieve a clear acoustical separation of the instruments.

IV. PILOT STUDY

Ten healthy participants (aged from 20 to 44 years; 5 female, 5 male) received full orchestral feedback of their brain activity from one channel of EEG (Cz versus C3). A ProComp+ portable amplifier was used with an EEG-sensor providing a frequency range from 0.01 Hz to 50 Hz at a sampling frequency of 256 Hz. Ag/AgCl electrodes were attached on the head.

The basic setting was used for sonification. SCPs were played by instrument no. 80 (ocarina) in the MIDI table. The delta band was represented by low pitches of instrument no. 47 (harp). Theta and alpha were played by instrument no. 12 (vibraphone) with the same base note. Easy to distinguish higher pitched instruments no. 98 and no. 101 were used for beta and gamma activity, respectively.

Initially, participants were instructed about the meaning of the different sounds. For this purpose, each instrument was played separately. After that, all instruments were played together and their volumes were balanced according to the participants' individual spectral power distribution. All subjects appreciated the characteristic timbres of instruments and found the stereo presentation helpful for distinction, e.g. between theta and alpha rhythms. None of them had problems with the sound complexity in the basic setting.

After a short time of adaptation the participants were introduced to the attention task. They were instructed to focus their attention alternately on two different sounds. The sequence of the tasks was defined by the computer in a balanced order and symbolized on a screen by two vertically arranged rectangles. A red colored upper rectangle asked participants to focus attention on the rhythmic vibraphone sounds (alpha, theta, and gamma). A red colored lower rectangle asked them to focus attention on the smooth sounds (SCP, delta, and beta). Each task symbol was presented for 8 seconds. After a two seconds resting interval the next trial began. 50 trials comprised one block of trials. Four blocks separated by short breaks were carried out in one session.

V. RESULTS

We evaluated task dependent variations of the parameters used for control of the POSER device. Significances are illustrated in Table 1. T-test revealed significant differentiation between the tasks at least in one parameter for all participants (highlighted in gray in the Table).

The highest variations were induced in the delta-band of subject P5 ($t(200)=9.21$, $p<0.01$). In a classification of the delta amplitudes, 80 % of all trials were classified in accordance with the task. In a second session with the same participant this regulative ability could be replicated with 85 % correct responses and a t-value of $t(150)=12.2$. Four participants revealed regulatory ability in more than one of the rhythmically presented frequency bands (P3, P4, P5, and P10).

Significant changes of the amplitudes in the alpha-band could be observed in six of the ten participants. Also beta and gamma power revealed significant differences in most of the subjects.

Significant regulation of the frequency of a rhythm was observed in three participants (P3, P5, and P7). Notably, P7 showed both a significant increase of alpha frequency (of about 0.2 semitones) and a decrease in theta frequency (of about 0.2 semitones) when paying attention to the smooth sounds. All three participants in addition modified at least one amplitude significantly.

No significant differentiation of the SCP amplitudes was seen in this pilot study.

Qualitative listening tests with the complex bi-hemispheric setting revealed that the EEG parameters presented in 11 voices could clearly be distinguished in a good stereo reproduction.

VI. Discussion

The device POSER allows on-line acoustic feedback of a variety of parameters from human EEG. Building on the previously introduced TTD environment, POSER constitutes a BCI with data acquisition, data storage, real-time signal processing and parametric sonification using the MIDI-system of a computer for sound generation. Having direct access to the MIDI-interface, POSER is available as a single program. The TTD offers a number of BCI applications for which POSER might be a new means of control.

The decomposition of the EEG signal into frequency bands is appropriate due to the different physiologic origins of the respective components. This decomposition allows us to extract differential parameters associated with each frequency band. Whereas previous BCI approaches have focused on the isolation of a single EEG parameter for feedback (like SCP or μ-rhythm), POSER employs a set of filters for the independent and parallel control of multiple parameters.

A crucial argument for the use of parametric sonification is that the frequency range 1-12 Hz can be most adequately represented in the frequency-time domain. In this range, the audible rhythms generated by triggering the touch on wave maxima directly represent the frequency of the band pass filtered wave. In addition, when the smooth wave form of the EEG signal is chopped into discrete events this is by no means arbitrary. Neurophysiologic research has confirmed that the smooth waves recorded with surface electrodes have their origin in discrete bursts of synchronized cortical activity and thus in an explicitly rhythmical process (see e.g. [13]).

The frequency assignment uses an arbitrarily chosen frequency as a base but preserves frequency relationships in the EEG recording both in the tone sequence of a single instrument ("melody") and in the momentary relationships between instruments ("harmony"). Continuous sounds were chosen for the SCP and the higher frequency bands to keep the rhythmic information within manageable perceptory bounds. The presence of two equally important classes of sounds (percussive and smooth) facilitates the voluntary shift of attention from one to the other.

The results of the pilot study with ten participants demonstrate that self-regulation of EEG parameters is possible with orchestral feedback. With the exception of SCP, each of the parameters was significantly modified by at least one participant. This confirms that in the frequency range 1-12 Hz the multiparametric representation of amplitude, frequency and rhythm was successfully exploited for information extraction. Significance of the regulation of beta and gamma band power should be treated with caution as these high frequencies are sensitive to muscular artifacts (e.g. an increase in tension). High positive correlations between beta and gamma activity such as found in P1, P3, P4, and P10 in combination with similarly high significances in the beta and gamma range may partly be due to muscle activity. In contrast, reverse regulation of beta and gamma band activity such as in P8 and P9 point to genuine brain wave regulation.

The lack of SCP regulation might be due to: a) the SCP sounds were rare and of low frequency and thus hard to discern in the chosen combination of instruments; and/or b) the task was not specific to SCPs and thus no particular attention was paid to the representing sounds. Both points can easily be addressed within POSER if SCP regulation is a desired goal.

The results show the existence of subject-specific control parameters without training. The significances of regulation vary strongly between participants. This is consistent with the fact that no training was provided and indicates individual processing of attentive listening to the complex sounds. One purpose of orchestral sonification is to provide multiple choices and to thereby enhance the chance of finding new interaction parameters for successful feedback. In this sense the results encourage specific training of the most promising parameters for advanced brain-computer communication. A criterion for the label "promising" is the repeated finding of significant control of a given parameter in successive sessions (as in the case of P5). Parameters that turn out to be suitable may then be tried for the communication with completely paralyzed patients who often have restricted visual abilities. If distinct EEG patterns can indeed be related to the state of auditory attention, the training may result in highly classifiable mental states. The TTD includes classification algorithms such as the linear discriminant analysis to create binary responses and thereby allows for direct brain-computer communication with the built-in spelling device. In this case, paralyzed patients might directly benefit from self-regulation of their brain potentials in the auditory paradigm.

It can be assumed, that the multiple electrode setting will improve the quality of parameter extraction. For instance, the alpha rhythm can be fed back from parietal and occipital areas where it is measured best whereas the theta rhythm can be chosen from a central or frontal position. Another advantage is the possibility to simultaneously monitor the activities of corresponding positions on the two hemispheres. The rhythmically represented frequency range is particularly suited for the detection of synchronization/desynchronization transitions in the course of an experiment. So far, these possibilities have not been exploited.

The use of the POSER device in a closed-loop feedback application leads to a new level of interaction with one's state of consciousness. The multi-parametric mapping generates complex, continuously evolving sound patterns. The complexity of electric brain activity is thus better represented than with devices that give only truncated or binary output. The aim of feedback training will now be to detect specific motifs in the continuous sound patterns that can be related to a mental state or to a change between mental states. In this task a subject no longer can focus on a single parameter in isolation but has to take the ongoing activity into account. The inclusion of ongoing activity of other parameters in an experiment that tries to train control of only one parameter might seem an unnecessary complication at first sight. However, once control of one parameter in the context of the others is successfully learnt, this implies experience with the management of its context-dependence.

We can only speculate whether listening to the brain's working via the orchestral sonification might be a way to learn something about the organization of brain activity. However, it is accepted that brains work as pattern recognition devices that first encodes all sensory information into multiple streams of neural rhythms and then uses rhythmic reorganization of its ongoing activity to process the input. A part of this reorganization that takes place in cortical nerve cell assemblies (i.e. near the scalp) might in principle be discernible from the spectrally resolved rhythms in the delta, theta and alpha band. It is even conceivable that by listening to real-time reproductions of these mostly cortical rhythms a brain can implicitly learn to associate sound patterns or motifs to specific states of consciousness, thoughts, or emotions. If so, one might even wonder whether one day it will be possible to deliberately generate pre-imagined sound patterns, i.e. "compose" with the aid of real-time orchestral sonification.

As a high learning success of self regulating EEG potentials is a sign of further improvement [7]; [16] we expect that some of the significant sonification parameters of this initial session can be used for direct brain communication or on-line composing of brain music with further training.

ACKNOWLEDGMENT

G.B. thanks the Institute for Medical Psychology at the University of Tübingen for an invitation in 2002, and Thomas Hermann for discussion. T.H. acknowledges support for a research stay at the University of Morelos from CONACyT (project no. 40885-F). We thank Niels Birbaumer for discussion.

REFERENCES

[1] N. Birbaumer, H. Flor, N. Ghanayim, T. Hinterberger, I. Iverson, E. Taub, B. Kotchoubey, A. Kübler, and J. Perelmouter, "A Spelling Device for the Paralyzed," Nature, vol. 398, pp. 297-298, 1999.

[2] T. Hinterberger, J. Mellinger, and N. Birbaumer (2003). The Thought Translation Device: Structure of a multimodal brain-computer communication system. Proceedings of the 1st International IEEE EMBS Conference on Neural Engineering, Capri Island, Italy, March 20-22, 2003, pp. 603-606.

[3] T. Hinterberger, „Entwicklung und Optimierung eines Gehirn-Computer-Interfaces mit langsamen Hirnpotentialen," Dissertation in der Fakultät für Physik an der Eberhard-Karls-Universität Tübingen, Schwäbische Verlagsgesellschaft, 1999.

[4] Sterman, M. B. (1977). Sensorimotor EEG Operant Conditioning: Experimental and Clinical Effects. Pavlovian Journal of Biological Sciences 12(2), 63-92.

[5] Wolpaw, J. R., and McFarland, D. J. (1994). Multichannel EEG-based Brain-Computer Communication. Electroencephalography and Clinical Neurophysiology 90(6), 444-449.

[6] Pfurtscheller, G., Flotzinger, D., Pregenzer, M., Wolpaw, J. R., and McFarland, D. (1996). EEG-Based Brain Computer Interface. Medical Progress through Technology 21, 11-121.

[7] T. Hinterberger , N. Neumann, M. Pham, A. Kübler, A. Grether, N. Hofmayer, B. Wilhelm, H. Flor, and N. Birbaumer, "A multimodal brain-based feedback and communication system," Experimental Brain Research, DOI 10.1007/s00221-003-1690-3

[8] G. Kramer (ed.), Auditory Display – Sonification, Audification, and Auditory Interfaces, Addison-Wesley, Reading 1994.

[9] G. Kramer, "Some Organizing Principles for Representing Data with Sound", in [11], p. 185.

[10] W.T. Fitch, G. Kramer, "Sonifying the Body Electric: Superiority of an Auditory Display over a Visual Display in a Complex, Multivariate System", in [11], p. 307.

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

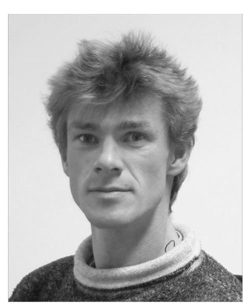
[12] T. Hermann, P. Meinicke, H. Bekel, H. Ritter, H.M. Muller, S. Weiss, "Sonifications for EEG data analysis", Proc. Int. Conf. on Auditory Display, publ. Int. Community for Auditory Display, pp. 37-41, Kyoto, Japan, July 2002.

[13] M. Steriade, "Cellular Substrates of Brain Rhythms", in: In: E. Niedermeyer and F. Lopes da Silva (eds.), Electroencephalography, 4th edition, Lippincott Williams & Wilkins, Philadelphia, 1999, pp. 28-75.

[14] T. Hinterberger, J. Kaiser, A. Kübler, N. Neumann and N. Birbaumer, "The Thought Translation Device and its Applications to the Completely Paralyzed," in H. Diebner, T. Druckrey & P. Weibel (eds.): Sciences of the Interfaces, Genista-Verlag Tübingen, pp. 232-240, 2001.

[15] G. Schalk, D. J. McFarland, T. Hinterberger, N. Birbaumer, and J. R. Wolpaw, "BCI2000: A GENERAL-PURPOSE BRAIN-COMPUTER INTERFACE (BCI) SYSTEM", submitted.

[16] N. Neumann and N. Birbaumer, "Predictors of successful self-control during brain-computer communication," Journal of Neurology, Neurosurgery, & Psychiatry, in press.



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