MULTI-CHANNEL SONIFICATION OF HUMAN EEG

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ABSTRACT

The electroencephalogram (EEG) provides a diagnostically important stream of multivariate data of the activity of the human brain. Various EEG sonification strategies have been proposed but auditory space has rarely been used to give cues about the location of specific events. Here we introduce a multivariate event-based sonification that, in addition to displaying salient rhythms, uses pitch and spatial location to provide such cues. Using clinical recordings with epileptic seizures we demonstrate how the spatio-temporal characteristics of EEG rhythms can be perceived in such sonifications.

[Keywords: Event-based sonification; epilepsy, spatio-temporal patterns]

1. INTRODUCTION

The electroencephalogram (EEG) consists of a group of parallel recordings of the electric potential from the human scalp [1]. Its most common display is the parallel arrangement of the recorded potentials as time series. Apart from a huge body of other visualization techniques there are some attempts of auditory displays for a scientific purpose in the literature (see e.g. [2,3] and references therein). While various specific aspects of the time series (like amplitude, variance, Fourier power) were considered previously, the question of spatial localization of events in the EEG has not been dealt with explicitly so far. This is surprising because the data represent not only the temporal but also the spatial dynamics of brain activity, and localization of patterns belongs to the most important criteria for the interpretation of specific events in clinical diagnoses [4]. For example, in epileptic EEG the localization (or distribution, respectively) of abnormal events in seizure-free epochs helps to locate the so-called epileptic focus, and the distribution of rhythms during a seizure helps to identify the type of seizure with direct implications for therapy.

On the other hand, it has been argued in the literature that one of the advantages of auditory displays over visual displays should lie in the way the human sense of listening deals with multiple events that arrive in one sound stream, and should thus be particularly suited for data mining and data exploration of multivariate data sets [5]. Sonifications that included spatial cues were attempted in the case of meteorological data [6]. In the medical area, there have been studies on effective multivariate auditory monitoring devices during surgery [7]. There seems to be no explicit medical applications of the auditory representation of space in the case of the human EEG.

Here we use a recently introduced event-based sonification of EEG rhythms to develop a multi-channel sonification that allows the listener to perceive spatial characteristics of the data in a multi-speaker environment. Examples of sonified transitions to epileptic seizures are presented. The possibility of a virtual auditory EEG environment with advanced spatial cues is discussed.

2. MULTIVARIATE EVENT-BASED SONIFICATION

Event-based sonification (EBS) was proposed as a simple and effective way to aurally represent rhythmic physiologic data [8]. For the case of so-called dynamic diseases (where a change of rhythmic characteristics is considered to indicate pathology, c.f. [9]) it was argued that this technique provides an efficient way to distinguish normal from abnormal rhythms (c.f. sound examples in [10]). With human EEG, a complex event-based sonification was used to characterize epilepsy [11], the epitome of a dynamic disease [12]. Recently, a simple but effective EBS for epileptic rhythms in the human EEG was introduced [13] and elaborated for its real-time application in clinical EEG monitoring and EEG feedback [14]. Based on the approach presented in [14], we propose a new representation of multiple EEG channels to provide the listener with spatial cues that can be interpreted in terms of spatial characteristics of the underlying brain dynamics.

The basic idea in EBS is to scan the data stream for features that are defined as events and then to use these events to trigger sound synthesis. Local maxima are events in the time series that are both suitable for real-time sonifications and meaningful to the clinician. We check for maxima with a three-point comparison in low-pass filtered data. A low-pass filtering at e.g. 30 Hz reduces the number of maxima detected and restricts the events to the part of the Fourier spectrum with the largest power. Typically, we expect epileptic rhythms in the frequency band from 0.5 to 20 Hz. Note that this band roughly coincides with the range of rhythm perception in humans and is thus suited for on-line sonification of the events.

We first explain the sound synthesis algorithms and then introduce the event-based mapping with spatial cues.

2.1. Sound Synthesis for Event-based Sonification

The sound synthesis is implemented in SuperCollider3, an open source package for real time audio synthesis programming. We start by defining the sound characteristics of two instruments with contrasting features. The first sound generatorm named 'HGrain', generates harmonic sound events:

```
SynthDef("HGrain",{|out=0, dur=0.2, amp=0.1,
        freq=300, numharm=5, att=0.002,
        pos=0, wid=2, orient=0|
var sig, env;
sig = Blip.ar( freq, numharm, 1, 0);
env = EnvGen.kr( Env.perc(att, dur, 1, -8),
        levelScale: amp, doneAction: 2);
Out.ar(out, PanAz.ar(~numChans, sig, pos,
   env, wid, orient))
}).load(s);
```

'HGrain' consists of a *Blip* oscillator (italics indicate objects of the programming language) with constant fundamental frequency. The *Blip* oscillator is a band-limited impulse generator where all harmonics have equal amplitude. The generated tone is modulated with a percussive envelope *Env.perc* that allows adjustment of attack time (the onset characteristics of a sound before the plateau is reached), duration of tone, and decay rate. Parameters of the *Blip* oscillator (amplitude, frequency, number of harmonics) and its amplitude envelope (attack, duration, decay) are available for control by features extracted from the time series.

The second sound generator, called 'NGrain', generates noise grains as follows:

```
SynthDef("NGrain", { |out=0, dur=0.05, amp=0.1,
      cf=900, rq=0.08, pos=0, wid=2, orient=0|
var sig, env;
sig = Decay2.ar(Impulse.ar(1, phase: 0), 0.0001,
      dur, PinkNoise.ar, 0);
sig = BPF.ar(sig, cf, rq, 10);
env = amp + Line.kr(0, 0, dur, doneAction: 2);
Out.ar(out, PanAz.ar(~numChans, sig, pos,
      env, wid, orient))
}).load(s);
```

'NGrain' uses a pink noise *PinkNoise* that is triggered by an *Impulse*. The temporal evolution of the spectral envelope is controlled by an exponential decay function *Decay2*. Finally the noise grain is band-pass filtered using *BPF* with a given center frequency and filter quality 1/rq. Here, the intensity at the onset and the decay time are controllable parameters.

The two instruments were designed for accurate timing. They allow to control pitch and duration characteristics, while realizing subjectively a good contrast in timbre.

2.2. Mapping in Event-based Sonification

A single data channel is treated similar to the event-based sonification proposed in [14]: each maximum in the time series triggers a sound, this time, however, from one of the two described sound generators. Thereby, the sonic event summarizes and communicates some local properties of interest in sound. Fig. 1 illustrates the definition of basic features used for the event-characterization.

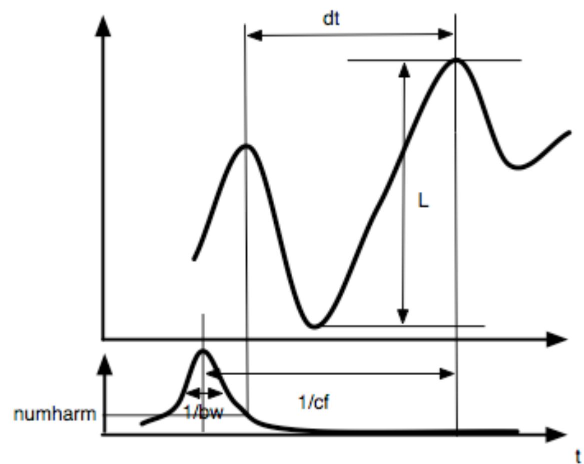

Figure 1. Parameters extracted from the time series for EBS mappings. The upper plot indicates a segment of time series. The lower plot depicts the Gaussian level characteristics used to select the "numharm" value, resp. the level for the noisy grains.

The volume level of an event in dB is set in a linear mapping of the voltage difference between the present maximum (that triggers the sound) and the previous minimum in a time series, denoted as *L* in Fig. 1. To avoid clipping artifacts due to the limited amplitude range of the synthesis engine, a constant maximum level is empirically adjusted for voltage differences that are larger than a given, data-dependent threshold.

The total duration of a tone, with fixed attack and decay rate, is modulated by the inter-maxima interval *dt*. This mapping was chosen to be linear, with short intervals leading to short and long intervals to long sounds.

The number of harmonics of a tone of 'NGrain' is controlled by the inter-maxima time interval with a nonlinear, bell-shaped function decaying to zero on both sides. The center of the function is placed at inter-maxima intervals that correspond to a typical epileptic rhythm in a given patient. The function is characterized by its center frequency *cf* and the bandwidth *bw*. Since clinicians often prefer to denote a rhythm in terms of its frequency rather than periods, the function is implemented as a Gaussian function in frequency space as shown in Fig. 1. Then, if a detected interval is of the length corresponding to this center, the largest number of harmonics is reached. Thus, a bright sound indicates the chosen frequency.

For the spatial arrangement of the output audio channels and for the assignment of the fundamental frequency of the *Blip* oscillator we use a coordinate system based on the modified 10-10 system of electrode positions on the scalp (Fig. 2).
The X-axis of this coordinate system is defined by the left-right extension on the scalp (ear to ear) and the Y-axis by the posterior-anterior line (neck to nose). Electrode Cz is placed at the origin (0,0).

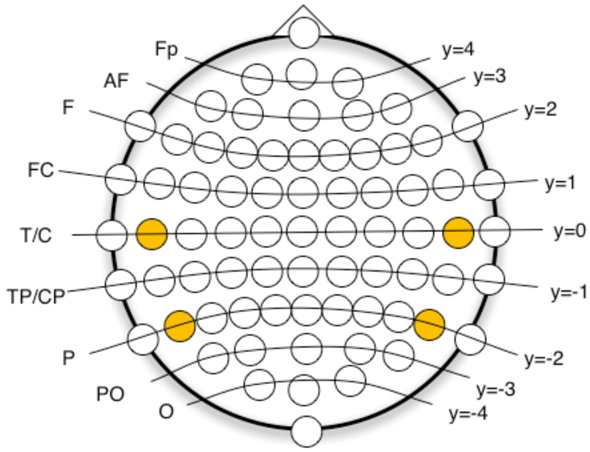

Figure 2. The 10-10 system of electrode positions on the scalp (viewed from top, nose up). The y-coordinates are shown on the right, on the left are the clinical labels for electrode rows. x-coordinates are defined accordingly.

For multivariate EEG sonification, we implemented a system to use arbitrarily large arrays of speakers. Currently, however, we assume a ring topology of speakers such that the sonification delivers cues about the azimuth position in the horizontal plane. Given the topographic channel layout as depicted in Fig. 2 and assuming the listener located at Cz, the sonification basically directs the listener's attention towards the appropriate angle. We currently use an 8-speaker setup. Practically, the spatial location of an electrode (X, Y) is used to compute the azimuth angle using atan2(Y, X). Distance is not reflected in a mix of opponent channels, but the signal is interpolated between those two audio channels that are closest to the intended location. The scheme works generically, including the stereo setup with N=2 as special case.

As spatial location does not permit unambiguous localization of electrodes (in particular in the stereo setting), we add pitch information as a clue about the Y coordinate of an electrode. The most posterior electrodes (O1 and O2) are assigned a base pitch and the Y coordinate of all other electrodes is then mapped linearly to pitch leading to highest pitch for the prefrontal electrodes Fp1, Fpz, and Fp2.

With the above-mentioned mappings and the HGrain oscillator we obtain a sonification that already delivers some auditory contrast between epileptic activity (long, loud, brilliant rhythmical sounds) and non-epileptic activity (dense, short arrhythmic textures of events). To enhance the possible emergence of auditory gestalts further, we introduce the noise grains that are particularly tuned to a second frequency of interest: similar as brilliance is optimized to be stronger with specific epileptic rhythms, the noise grains derive their amplitude value via a bell-shaped frequency-tuned mapping function with adjustable center frequency and bandwidth. This, for instance allows analyzing EEG data for the occurrences of rapid beta activity at the beginning of focal onset epileptic activity. As a result, the noise grains will generate salient rhythmical patterns if the data comply with predefined characteristics. This idea can easily be generalized towards a larger set of different grain streams tuned to specific data-driven characteristics. Such generalizations will be reported elsewhere.

The following code summarizes our mappings, with self-explanatory variable names. It furthermore shows how events are instantiated.

```
dtLastMax = (step - oldMaxPos[iC])/srate;
amp = (vecprv1[iC]- lastMinVal[iC]).linlin(
      0, 10, -50, -4).dbamp;
freq = (chypos[iC].linlin(-2,5,50,85)).midicps;
val = atan2(chypos[iC], chxpos[iC]);
pos = val.linlin(-pi, pi, 0, 2);
val = (((1/dtLastMax)-cf1)/bw1).squared.neg.exp;
numharm = val.linlin(0, 1, 2, 30).round;
if(1/dtLastMax<10){
  Synth.new("HGrain", [\out, 0, \amp, amp, \freq, freq,
    \numharm, numharm, \dur, dur, \pos, pos,
    \orient, orient]);};
val = ((1/dtLastMax-cf2)/bw2).squared.neg.exp;
dur = val.linlin(0, 1, 0.01, 0.15);
amp = val.linlin(0, 1.0, -50, 4).dbamp;
if(1/dtLastMax>0){
   Synth.new("NGrain", [\out, 0, \cf, 4*freq,
   \amp, amp, \pos, pos, \dur, dur, \orient, orient]);
};
```

3. CLINICAL DATA

EEG samples were recorded at the Neuropediatric Clinic of the University of Kiel from patients with two representative types of epilepsy. The first type, represented by patient 1, is the generalized absence seizure, where no particular onset zone of the seizure can be identified. The second type, represented by patients 2 and 3, is the focal onset seizure, where epileptic activity originates in a specific location or focus. In the case of patients 2 and 3, the focus is located in the frontal lobe. EEGs of patient 1 were recorded with 10/20 position of 19 scalp electrodes at a sampling rate of 256 per second. EEGs of patients 2 and 3 were recorded with 10/10 position of 27 scalp electrodes at a rate of 2000 (patient 2) or 500 (patient 3) samples per second. In all cases the data were band-pass filtered (low pass filter 30 Hz, high pass time constant 0.1 sec) before entering the sound synthesis. Data were used in a source density montage, which creates an individual reference for each electrode defined as the weighted sum of the potentials from its nearest neighbors. This reference acts as a spatial high-pass filter that improves localization and reduces spurious cross-correlations compared to common references, particularly in the case of generalized rhythms.

4. RESULTS AND DISCUSSION

Our first sonification example, Sound S1, is produced from eight channels of an EEG section in patient 1 with a transition from background activity to an absence seizure. We chose a reduced speed of about 2/3 of real time to allow the listener to perceive some details of the multivariate sonification. For EBS of a single electrode the reader is referred to [13]. The background activity is almost exclusively dominated by sounds from the NGrain generator tuned to a frequency of 14 Hz. The sound characteristics (driven by EEG parameters *dt* and *L*) reflect the large variability and noise-like properties of the time series. Rhythmic relationships between events in different channels are occasionally suggested but not confirmed and as such probably due to random correlations. The onset of the seizure is marked by the intrusion of pitched sounds from the HGrain generator (tuned to 3 Hz). These events start in individual channels, grow rapidly in intensity and are soon heard from all channels. This is accompanied by a dramatic change in rhythm from the mostly stochastic background to the nearly periodic seizure activity. The sounds from the NGrain oscillator join the seizure rhythm almost from its very onset. In the course of the seizure the rhythm maintains its global properties. Notably the frontal electrodes (high pitch) and rear right electrodes (low pitch) are synchronized among themselves and out of phase to central and rear left electrodes. However, there is also some perceptible evolution in detail. Firstly, the main frequency slowly decreases. Secondly, various electrodes undergo variations in the number of harmonics reflecting variation of the inter-maxima distances. Thirdly, in a group of rear electrodes (lower pitch) there is a trend from highly synchronized events to an arpeggio-like structure indicating growing phase delays. This 8-channel sonification already confirms the need for improved spatial cues for the differentiation of the rhythmic complexity.

An EBS with all 19 electrodes of the recording is presented in Sound S2. Fig. 3 shows the corresponding time series of the EEG time series. This sample is in real-time and thus represents the seizure as it would be heard in an on-line sonification. Here, we have generated a multi-channel output that can be displayed on a multi-channel speaker system.

In spite of the filtering in NGrain the sonification leads to a dense auditory stream for background activity (up to second 59 in Fig. 3), which is then interrupted by the epileptic activity. The epileptic rhythm has the dominant frequency of about 3 to 2.5 Hz with large amplitudes in most channels. Inspection of Fig. 3 reveals that even the time series O1 and O2 contain this rhythm albeit at smaller amplitudes. With its rhythmic features, as well as a marked beginning and end, the seizure activity creates a clearly perceptible auditory object.

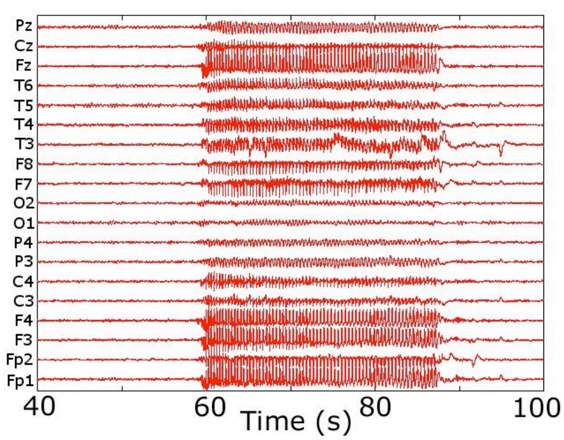

Figure 3. Time series of 20 EEG channels recorded from a patient with generalized epilepsy. The seizure occurs between 59 and 87 seconds.

The sound synthesis algorithm brings the typical features of this type of seizure to the foreground. The repetitive rhythmic motifs described for S1 also dominate the sonification of the complete EEG, S2. The texture of the composite sound is dense as the rhythm is picked up with different inter-electrode delays, which probably reflects propagation of activity waves in the cortex. This clarifies that the "hyper-synchronicity" of electric activity, which is often taken to be the landmark of these kinds of seizures, does not mean exact synchrony in the physical sense of "same phase". Nevertheless, the clinically known conservation of dynamics features within and across patients makes the absence seizure easy to detect and identify in the auditory setting.

Sound 3 is a sonification of an EEG section with seizure activity from patient 2 with frontal epileptic focus. These seizures differ from the generalized seizures in that the onset is less abrupt and more localized. The sound starts a few seconds before the onset of the seizure. In that initial section the noisy beats with a center frequency on the border between the alpha and the beta band (*cf2*=13 Hz) dominate. Just prior to the seizure the beta beats intensify in some channels. The seizure initiates with low volume pitched sounds (*cf1*=1 Hz) in a few channels. Then the volume increases and pitched sounds are audible. The epileptic waves are represented by groups of pitched sounds revealing their strong correlation. However, the clusters in this case are less rigid than in the absence seizure Sound 2.

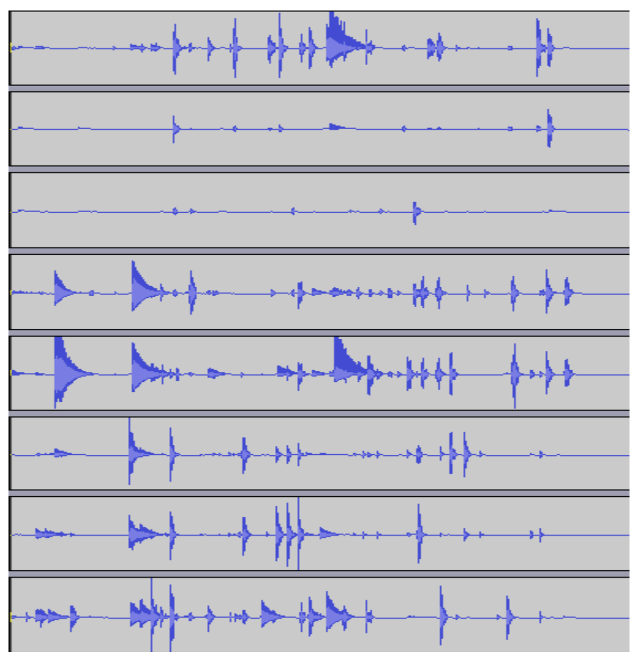

Figure 4. Audio Signals of 8 output channels synthesized from 20 EEG channels.

Next we compare two handpicked subgroups of channels from those used in Sound 3. For Sound 4 we have left the mapping and parameters identical to Sound 3 but sonified only 4 channels. In Sound 4a the four channels are [Fp2, F4, C4, P4], all from the right hemisphere. The resulting sound has some alpha and beta activity initially but this activity is significantly reduced during the seizure. With the end of the seizure it resumes, albeit weakly. During the seizure interval only few pitched sounds can be discerned but they are of low intensity and do not display the rhythmicity heard in Sound 3. These channels do not pick up the prominent epileptic rhythm properly.

In Sound 4b four other channels, [F10, T10, F8, T8], also from the right hemisphere, are sonified. The alpha/beta beats set in, get slightly more intense, then suddenly stop with the start of the seizure. The seizure is displayed by pronounced epileptic pitched sounds with organized rhythmicity. This spatial differentiation is typical for a given patient and reflects both the location of the epileptic focus and the cortical area that is most affected by the spreading of epileptic activity. It turns out, however, that the stereo display of all channels of Sound 3 does not support the spatial differentiation well.

We therefore turn to multi-channel audio output for the sonification of this segment. Sound 5 displays again all channels of the EEG as in Sound 3 but this time with 8 audio output channels that we suggest to be positioned in a ring around the listener. Fig. 4 shows a segment of the eight resulting sound waves. In the left third of the segment there is an event that can be heard from the 5 speakers at the bottom of the figure, whereas it is not heard in the upper three speakers. At about the center of the figure is an event that occurs synchronized in speakers 1 and 5 (from top). In this way, the assignment of different electrodes to different audio channels provides clear spatial cues about the sources of events and about relationships between sourced. This significantly improves the perception of the groups of electrodes that generate the epileptic rhythm and allows a straightforward differentiation from those that do not. Together with the rhythmic organization of the data flow this display gives detailed information about the spatio-temporal dynamics of the seizure.

Sound 6 is a sonification with the mapping used in Sounds 3 and for but for another patient, patient 3, with frontal focus. The pre-ictal section is again a dense layer of multiple noisy beats with parameter *cf2* at the border of the alpha and beta band. Here the first occurrences of pitched sounds are hardly audible, and they are strongly localized. Then more channels join in and occasional bursts of pitched sounds from various electrodes come in clusters. The duration between clusters is longer than in Sound 3. Towards the end they tend to start in a fronto-central location (where the focus as suspected) and spread particularly to the left hemisphere. Even though there are less pitched events and the rhythm is slower than in Sound 3, the sonification allows a good separation of background from epileptic activity. With a circular arrangement of the speakers the spatial distribution of the sources offers intuitive clues about the location of the responsible electrode on the scalp.

We suggest that the spatial arrangement does not necessarily need to reflect the geometry of the electrode arrangement on the scalp. In particular, if the sonification is applied to the EEG of a patient with some known epileptic features the spatial cues can be optimized by other considerations. First, as done already in some of the present sonifications, a selection of electrodes can be made, for example leaving out those that do not show epileptic characteristics in a given patient. Second, if the same focal activity is picked up by various electrodes, these tend to display the same rhythm either correlated or anti-correlated (due to phase reversal of the source dipole) and can therefore be combined linearly to allow a better signal-to-noise ratio [14]. Thirdly, if neighboring electrodes pick up different activities, they can be separated maximally in space to allow more comfortable differentiation of their respective locations. And finally, if the set of recordings can be divided into two groups (for example in partial seizures where only one hemisphere picks up the epileptic rhythm) the pitch range can be restricted to the involved electrodes instead of being spanned over the whole set. If the epileptic rhythm comes in clusters, as is often the case, c.f. Sounds 3 and 6, this allows better distinction of nearby electrodes by pitch.

The multi-channel sonification introduced here offers effective means to listen to human EEG for a scientific or medical purpose. Using filter characteristics it is possible to separate activity of interest from the background. The seizure initiates with low volume between 0.1 and 20 Hz the event-based display is intuitive in real-time applications like EEG monitoring or EEG feedback. The use of two (or more) contrasting sound generators allows a subdivision of spectral ranges of interest by adjustment of the parameters *cf1*, *cf2*, *bw1*, and *bw2*. And last but certainly not least, the inclusion of 360 degrees spatial cues permits the parallel sonification of many or all electrodes without loosing clarity in the display.

As a concluding remark, we believe that the inclusion of spatial aspects in multivariate sonification is still in its infancy as far as medical applications are concerned. Recently, source localization methods for EEG were developed that provide good estimates of the 3D coordinates of the sources of normal and pathologic activity [15]. We clearly foresee (or better: forehear) an advanced auditory virtual environment where not only surface position but the full 3D information is represented in event-based sonifications or other sonifications and which allows the listener to create and study a full spatial representation of the spatio-temporal dynamics of the human brain.

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LIST OF SOUND FILES

All sounds can be downloaded from the webpage:
http://www.sonification.de/publications

Sound S1: Event-based sonification of an EEG section of patient 1 with generalized absence seizure. Reduced speed, approx. 2/3 of real time. 8 channels from electrodes [Fp1, Fp2, F3, F7, F8, P8, FZ, PZ]. Filter tuning: *cf1*=3.0, *bw1*=2.5, *cf2*=14.0, *bw2*=3.5. Stereo.

Sound S2: EBS of the EEG section in sound S1 with generalized absence seizure. Real-time (256 samples/s). All 19 electrodes of the 10-20 standard EEG [Fp1, Fp2, F3, F4, C3, C4, P3, P4, O1, O2, F7, F8, T7, T8, P7, P8, Fz, Cz, Pz]. Filter parameters as in S1. Stereo.

Sound S3: EBS of EEG section with focal onset seizure in patient 2 with frontal focus. Real-time. 20 electrodes in the modified 10-10 standard [FP2, F10, T10, F8, T8, P8, F4, C4, P4,

FPZ, FZ, CZ, FP1, F3, C3, P3, F7, T7, P7, F9]. Filter tuning: *cf1*=3.0, *bw1*=2.5, *cf2*=14.0, b*w2*=3.5. Stereo.

Sound S4: EBS of EEG section with focal onset seizure of patient 2 as in Sound S3. Real time. **S4a**: Electrodes [Fp2, F4, C4, P4]. **S4b**: channels [F10, T10, F8, T8]. Filter tuning as in S3. Stereo.

Sound S5: EBS as in S3, except: 8 channel audio output.

Sound S6: EBS of EEG section with focal onset seizure in patient 3 with frontal focus. Real-time. 20 Electrodes in the 10-10 standard [FP2, F10, T10, F8, T8, P8, F4, C4, P4, FPZ, FZ, CZ, FP1, F3, C3, P3, F7, T7, P7, F9]. Filter tuning: *cf1*=3.0, *bw1*=2.5, *cf2*=13.0, *bw2*=2.5. 8 channel audio output.

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