# SONIFIED EPILEPTIC RHYTHMS

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**ABSTRACT**

We describe techniques to sonify rhythmic activity of epileptic seizures as measured by human EEG. Event-based mapping of parameters is found to be informative in terms of auto- and cross-correlations of the multivariate data. For the study, a group of patients with childhood absence seizures are selected. We find consistent intra-patient conservation of the rhythmic pattern as well as inter-patient variations, especially in terms of cross-correlations. The sound synthesis is suitable for online sonification. Thus, the application of the proposed sonification in clinical monitoring is possible.

## 1. INTRODUCTION

Epileptic seizures manifest themselves as spontaneous or induced disorder-order transitions in human electro-encephalogram (EEG). Multiple electrodes placed on the scalp record temporal potential variations caused by fluctuation in a spatio-temporal pattern of electric nerve cell activity, primarily in the cortex, the part of the brain that lies closest to the scalp. The irregular disordered pattern of normal (ongoing) brain activity turns into a globally ordered rhythmic pattern in the case of the so-called generalized seizures [1]. On the neural level this corresponds to a dramatic change in the degree of synchronization of the firing between neighboring and widely separated neurons [2]. As a consequence, the EEG time series display sharp changes in (temporal) autocorrelations and (spatial) cross-correlations.

It has been argued that sonification provides an intuitive way to investigate whether irregular physiologic rhythms are deterministic or stochastic in nature [3]. In particular, event-based sonification is a means to detect short-term autocorrelations if the mean period between two events is in the range where rhythms are best processed by the human ear, approximately from 0.5 to 10 Hz. This was first applied to human EEG in a sonification of an epileptic seizure in [4]. Recently, it was argued that in addition to aiding the characterization of autocorrelations, event-based sonification can be extended to facilitate the detection of cross-correlations [5]. In this case the aural perception is especially sensitive to transient changes in spatial correlation. Taken together, these advantages suggest event-based sonification as an appropriate strategy to deal with multivariate time series of spatio-temporal physiologic patterns that show transient changes in either auto- or cross-correlations, or both.

Here, we describe a method to create event-based rhythms from multivariate human EEG and demonstrate sonifications of epileptic activity that are suitable for real-time implementations like clinical monitoring.

## 2. THE DATA

Clinical EEGs were recorded with standard 10/20 positioning of 19 scalp electrodes from children with diagnosed primary generalized absence seizures of 3 Hz spike-and-slow-wave appearance. The sampling rate was 256 data points per second, and the recording equipment performed default high-pass filtering (>0.5 Hz). For the present purpose, samples of several minutes length were selected from pre-recorded EEGs. These included at least one sudden transition from apparently normal to seizure activity.

Data were transformed with the Hjorth source derivation [6]. The Hjorth montage creates an individual reference for each electrode defined as the sum of the potentials from nearest neighbors. It thus acts (like any current source density montage) as a spatial high-pass filter that reduces spurious cross-correlations that stem from the spreading of the electromagnetic field of a dipole at some distance from it. No other manipulations of the data were performed prior to sound synthesis.

## 3. THE SONIFICATION

For sonification the complete 19 channel EEG data were loaded as comma separated voltage values and a fixed number of channels was selected. Each of the selected channels was treated equally. We describe the two-channel setting in detail; sonifications with a larger number of channels are done by trivial extensions of this core setting.

In epileptic EEG the extrema of the time series (minima and maxima) are natural candidates for “events”. Zero-crossings and inflection points are other choices but we found no improvement in the sonification result and thus keep the selection of time series maxima as events for the examples discussed in this contribution. For data that are filtered for 50Hz AC contamination, a three-point criterion to find maxima is sufficient but for AC contaminated raw data a five- or even seven-point criterion with its smoothing effect is superior for rhythm generation.

Each maximum triggers the playing of a sound from a predefined *synth* in Supercollider. The *synth* consists of a *blip* oscillator with constant fundamental frequency and added sinusoidal vibrato. The tone is modulated with a percussive envelope that allows adjustment of attack, duration and decay. Parameters of the *blip* oscillator (amplitude and number of harmonics) and its envelope (duration) are controlled by time series features.

The **volume** of a tone is set by mapping of the voltage difference between the present maximum (that triggers the sound) and the previous minimum in the same time series linearly to the amplitude of the oscillator. The **duration** of a tone is modulated by the inter-maxima interval, i.e. the period between the present and the previous maximum. Again the mapping is linear and consequently a short period leads to a short tone and long period to a longer tone. The **number of harmonics** of a tone is controlled by the period between the present maximum in a given time series and the previous maximum in another time series. The mapping is reciprocal, i.e. a short distance between maxima leads to a high number of harmonics (a sharp tone) and a long distance results in a low number. In all parameters the mapping is bound to a finite range with prefixed limits set to keep the sound within reasonable boundaries (e.g. maximum volume, no zero or negative number of harmonics, etc.). The fundamental frequencies of each oscillator are fixed, for the two channel examples presented here, $f(1)=100$ Hz and $f(2)=150$ Hz were chosen to create a harmonic and non-disturbing impression for listeners with little experience in aural data-dependent representations.

In the two-channel setting, channels are panned to the left and right stereo speaker by means of the 2-channel equal power panning *pan2* in Supercollider, respectively. More than two time series can be used, but with four or more sound sources a four channel pan is preferable.

## 4. RESULTS AND DISCUSSION

Whereas spontaneous EEG is of comparatively low amplitude and highly irregular, the epileptic EEG in the case of absence seizures is of high amplitude and regular. Fig. 1 shows a zoom of the epileptic activity in two EEG channels.

The lower trace of Fig. 1, electrode F4 over the right hemi-sphere of the frontal cortex, displays the typical spike-wave complex which results in two (positive) dominant maxima separated by low-voltage irregular activity during the slow wave phase. The complex repeats with a periodicity of approximately 0.4 seconds resulting in a dominant frequency of about 2.5 Hz in this section of the attack. The upper trace (electrode T4 over the right hemisphere of the temporal cortex) similarly shows a periodic pattern with two dominant maxima. The two signals are strongly anti-correlated. Thus strong auto- and cross-correlations are present during the epileptic attack.

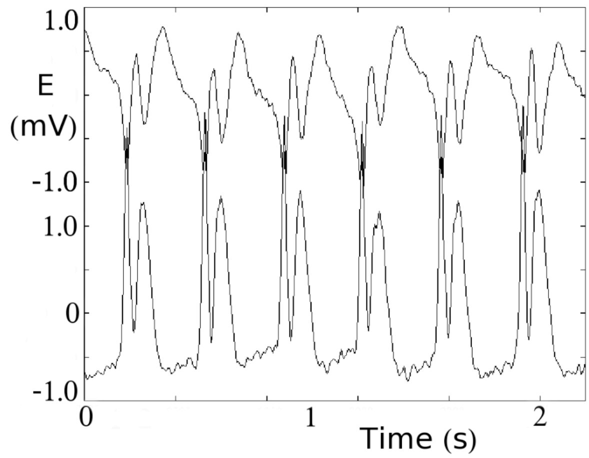


Figure 1: Electrode T4 (top) and F4 (below) as a function of step number (256 samples per second). The signals show spike wave complexes as discussed in the text. This corresponds to sound example S1.

The sonification example S1 gives an impression of the rhythms in the two time series (as displayed in Fig 1) at reduced speed. At this speed the individual beats can be clearly discerned separately and the effects of the volume, duration and number of harmonics control can be understood. The sudden change of brightness that occurs occasionally in the fourth beat of the repetitive four-beat complexes (in the channel with higher fundamental frequency, electrode T4) is due to an additional maximum near the baseline of time series of F4 after a spike-wave complex. This effect is perhaps undesirable as it is due to background activity. It can easily be avoided by choosing only positive maxima if pure spike-wave behavior is to be heard in the sound. In any case, the grouping of the beats and its sound characteristics are clearly pronounced to produce an easy-to-identify rhythmic pattern in a real-time display.

Sound S2 contains a section of background EEG followed by a complete seizure in real-time. Onset and offset of the seizure are clearly marked by volume, rhythm and tone characteristics of the sound. Whereas in example S1 the effect of each control parameter could be listened to with little effort, these features merge in the real-time display to form a coherent auditory object that represents the epileptic seizure. The seizure sets in with 4 three-beat complexes, after which the typical four-beat complex dominates. There is a slight slowing-down of the overall pulse and then the seizure terminates abruptly. After this, background activity resumes.

Example S3 is a sonification of another EEG segment containing background activity and seizure of the same patient. It is generated with exactly the same parameters as S2. There is a short block of seizure-like rhythm followed by a background break before full seizure activity initiates. Even for untrained listeners, the latter can be recognized as the "same" rhythm as in S1, despite some slight modifications. Interestingly, the seizure here initiates with some three-beat complexes, just as in S1. In various other patients we have found this almost stereotyped seizure pattern when different instances are played from the same patient. In addition, we made the same sonification with seizures from three more patients, and find that the difference are remarkably small. Thus, in this preliminary study we hear low intra-patient as well as inter-patient variation of the rhythms during absence seizures in children. However, it has to be stressed that our patients were selected because they show only one epileptic EEG symptom. In more complex cases the results may differ substantially.

The rhythmic pattern depends on the combination of electrodes chosen for the sonification. For example, contra-hemispheric electrodes often show strong correlation due to direct neural connections. Thus, if electrode F4 is combined with contralateral electrode F3, the synchronization between hemispheres yields a rhythm that is not much different from that of each of the channels played independently. Sonification S4 is the corresponding example. The sharp sounds indicate the small temporal differences between maxima in the two channels.

In one patient we found that frequently the spike-wave activity was preceded by bursts of rapid spikes. Thus, visibly there are two pronounced features in the EEG. Fig. 2 shows a time series that includes both.

There are 6 bursts in the first half of the selected period followed by a transition period that then leads to spike-wave complexes. Sound S5 is generated from this patient and includes the section shown in Fig. 2. The important feature here is that the two visibly distinct features have their auditory counterpart that allows unambiguous identification while listening to the EEG. When rhythms with different dominant frequencies are involved in one channel, the control of tone duration is of particular importance. A long tone gets blurred when repeated too rapidly and too short tones render a weak rhythmic impression when played with long intervals.

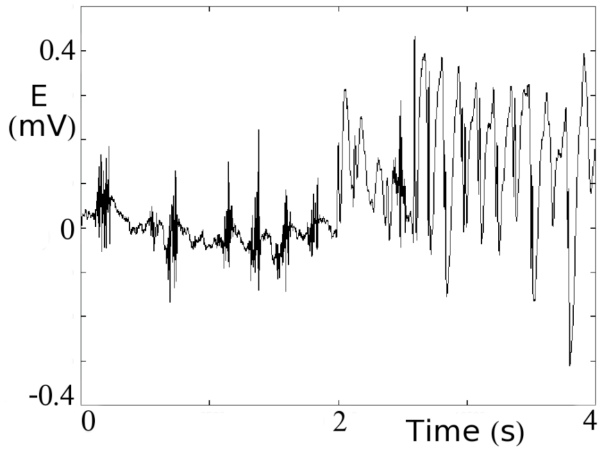


Figure 2: EEG time series at the start of epileptic activity, some bursts can be discerned. The plot accompanies sound example S5.

The sonifications provided yield clear results when the EEG rhythms are in the optimal range for auditory rhythm perception as is the case in absence seizures. If rhythms are expected to be outside this range, the sonification strategy has to be modified slightly. As an example we mention that for fast rhythm only every n-th maximum can be played or that n maxima can be summed before a tone is triggered. For very slow rhythms it is possible to trigger two or more tones in sequence with decreasing amplitude (echo effect) thus filling the gaps.

If the amplitude of a rhythm has a mean that is within the variance of the background, the sharp volume-dependent edges of the auditory objects discussed above are lost. The additional information is required to detect the onset of the rhythm as soon as possible to allow similar volume control. A method to obtain this information has been suggested in [7], where an excitable medium is continuously perturbed with the EEG time series and acts as a fast-reacting band-pass filter. With this technique it is even possible to cover a wide range of frequencies and thus sonify a spectro-temporal decomposition of each channel [8].

For a real-time application as e.g. clinical EEG monitoring, one fixed set of sonification parameters might not be enough. Rather, one would have the opportunity to adjust the sonification interactively according to e.g. the state of the patient, the pathologic features searched for, the amount of artifacts, etc. To this end we intend to provide a graphical user interface for real-time interaction with the main parameters involved in the sound rendering.

To tune the proposed sound synthesis parameters to optimal values, a validation of the sonifications by target listeners has to be performed. This is of importance to accelerate the learning phase for the recognition of epileptic rhythms and for the differential perception of normal rhythms, pathologic events and recording artifacts.

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## 5. LIST OF SOUND FILES

All sounds can be downloaded from the following webpage:
http://www.techfak.uni-bielefeld.de/~thermann/projects/index.html

**Sound S1**: Event-based sonification of time series from electrode F4 (left channel, fundamental frequency 100 Hz) and T4 (right channel, ff 150 Hz) during absence seizure. 6-fold reduction of speed compared to real-time.

**Sound S2**: Sonification as in S1, except speed is real-time.

**Sound S3**: Sonification as in S2 of another segment of EEG with absence seizure from the same patient.

**Sound S4**: Sonification as in S2, except that electrode T4 is replaced with F3 (contra-hemispheric to F4).

**Sound S5**: Sonification as in S2 with subclinical epileptiform activity from another patient. Electrodes used are C4 and T4.

## 6. REFERENCES

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