# **Slow Wave Dysfunction and Paroxysm Sound Detection:** A case study of EEG data sonification in two patients with epilepsy

Nikola Ivančević, Nebojša Malešević, Borjana Valčić, Jelena Ćertić, Milica M. Janković, Dejan Stevanović, Blažo Nikolić, Mirjana B. Popović, Jasna Jančić

***Abstract* — A parameter mapping sonification method can be used to convert EEG data into a sound. Sound equivalents of different EEG changes could help clinicians during EEG recording, monitoring and analysis. This method could also be used in home surveillance systems in people with epilepsy. We present an example of using a parametric based algorithm for epileptic discharge detection by non-expert listeners with short pre-training. The algorithm was applied onto data collected from two patients with epilepsy and different EEG abnormalities.**

***Index Terms* — Sonification, Epilepsy, EEG**

## I. Introduction

### A. *Sonification techniques*

One of the approaches to electroencephalographic (EEG) data analysis is translating it into a sound domain and exploiting high sensibility of the auditory system [1]. Idea of converting EEG signal into the sound is actually almost old as EEG technique itself and dates to early 1930s when Edgar Adrian listened to his own EEG signal [2].

According to the International Conference on Auditory Display (ICAD), sonification represents "the use of non-speech audio to convey information; more specifically sonification is the transformation of data relations into perceived relations in an acoustic signal for the purposes of facilitating communication or interpretation" [3].

There are various methods for converting EEG signals into a sound such as audification, parameter-mapping sonification (e.g. event based, vocal sonification, and hybrid models), model-based sonification, and generative music [4].

*Audification* technique includes amplification and temporal compression of EEG data resulting in the sound spectrum shifted to a suitable audible range [4, 5]. *Parameter-mapping sonification* method is mapping values of a selected measured variable to a sound synthesis parameter: frequency, brightness, or amplitude [1, 4, 6]. *Event-based sonification* uses some relevant EEG events of interest extracted from the underlying data and then represents them by sound [7]. *Vocal sonification* technique converts specific EEG signal features into vowel sounds, especially combination of a-e-i [8]. *Hybrid models* combine some of previous sonification models [9]. *Model-based sonification* uses mathematical models which generate sound according to EEG data input [4]. *Generative music systems* use musical rules to create sound output using EEG data as a control signal. Example of this is using music in brain-computer interface paradigm (BCI), named brain-computer music interface (BCMI) [4, 10].

### B. *Epilepsy and EEG*

Between 34 and 76 new cases are diagnosed per 100,000 people every year [11]. In pediatric populations, epilepsy is one of the most common neurological disorders, with an incidence rate of 45/100,000 per year [11].

According to the International League Against Epilepsy (ILAE), epilepsy is a disease of the brain defined by any of the following conditions: 1) at least two unprovoked (or reflex) seizures occurring > 24 h apart; 2) one unprovoked (or reflex) seizure and a probability of further seizures similar to the general recurrence risk (at least 60%) after two unprovoked seizures, occurring over the next 10 years; 3) diagnosis of an epilepsy syndrome [12].

As a complication of epilepsy, status epilepticus is prolonged epileptic seizure (more than 5 minutes) and it has a high mortality, from 3% in children up to 30% in adults [13]. Unrecognized and untreated epilepsy, despite status epilepticus, has high morbidity leading to psychological and emotional disturbances, or cognitive changes [11]. A serious acute complication in people with epilepsy is sudden unexpected death in epilepsy (SUDEP), which can affect individuals of any age, bur mostly young adults aged 20–45 years [14].

Nikola Ivančević is with the Clinic of Neurology and Psychiatry for Children and Youth, Faculty of Medicine, University of Belgrade, Serbia (e-mail: ivancevicsd@gmail.com).

Nebojša Malešević is with the School of Electrical Engineering, University of Belgrade, Serbia and with the Department of Biomedical Engineering, Lund University, Lund, Sweden (e-mail: nebojsa.malesevic@etf.rs).

Borjana Valčić is with the Faculty of Music, University of Arts in Belgrade, Serbia (e-mail: valcicborjana@gmail.com)

Jelena Ćertić is with the School of Electrical Engineering, University of Belgrade, Serbia (e-mail: certic@etf.rs).

Milica M. Janković is with the School of Electrical Engineering, University of Belgrade, Serbia (e-mail: piperski@etf.rs).

Dejan Stevanović is with the Clinic of Neurology and Psychiatry for Children and Youth, Faculty of Medicine, University of Belgrade, Serbia (e-mail: stevanovic.dejan79@gmail.com).

Blažo Nikolić is with the Clinic of Neurology and Psychiatry for Children and Youth, Faculty of Medicine, University of Belgrade, Serbia (e-mail: blazonikolic87@gmail.com).

Mirjana B. Popović is with the School of Electrical Engineering and Institute for Medical Research, University of Belgrade, Serbia (e-mail: mpo@etf.rs)

Jasna Jančić is with the Clinic of Neurology and Psychiatry for Children and Youth, Faculty of Medicine, University of Belgrade, Serbia (e-mail: jasna.jancic.npk@gmail.com).

Epilepsy is a clinical diagnosis, but EEG is the most valuable technique in defining and monitoring epilepsy. In clinical settings, the most commonly used is 16- to 21 channel-EEG with 10-20 -electrode placement system using from 18 to 21 electrodes with one ground electrode [15, 16]. EEG frequency bands are divided into delta (0.1 – 3.5 Hz), theta (4 – 7.5 Hz), alpha (8 – 13 Hz), beta (14 – 35 Hz) and gamma (35 – 70 Hz) [16, 17].

Abnormal slow rhythms on EEG are characterized as focal or generalized, rhythmic (monomorphic) or polymorphic (arrhythmic), intermittent or continuous, and in terms of the dominant frequency (delta or theta). They can be signs of serious brain pathology such as epilepsy, stroke, tumor, infection, metabolic disorders, or brain trauma [18, 19, 20].

### C. EEG data sonification in epilepsy

Auditory representation of EEG data is at this moment in development for clinical usage in the field of epilepsy monitoring and treatment [4-7]. Aldo the visual guided EEG data analysis is well established and has the long tradition, it could benefit in future combined with auditory input, especially for long-term on-line or off-line epilepsy monitoring and also in potential treatment using biofeedback paradigms [21]. Auditory perception of EEG data in biofeedback/epilepsy monitoring paradigms is suitable for few reasons: a) EEG seizure patterns and music sounds both have pronounced frequency patterns; b) humans are capable of focusing on particular sound in noisy environment ("the cocktail party effect") and c) listening to the music could be more motivating than just leaning on the visual guidance [21].

### D. Potential use of sonification techniques

EEG sonification techniques can be used for real-time EEG *monitoring* (e.g., brain state monitoring during surgery anesthesia, EEG monitoring in neonatal intensive-care unit or home seizure detection systems in people with epilepsy), *diagnostic* purposes (e.g., epileptic seizure detection in prerecorded data), *neurofeedback*, *BCI/BCMI*, and others [4].

### E. Aim of the study

The aim of this study was to test feasibility of a parameter-mapping sonification algorithm in epileptic discharge detection. This algorithm (earlier presented by N. Malešević [22]) was applied onto EEG samples from two patients with epilepsy and it was tested in an e-mail survey with lay persons.

Our long term goal is to develop the real-time sonification algorithm which could be used by experts and non-expert listeners in epileptic EEG discharges detection with minimal pre-training. We tend to generate rather "pleasant" sound for long term EEG data analysis, which could be used as a sole method in seizure detection or as an auxiliary method to the visual EEG analysis.

## II. Subjects and Methods

The first subject was a female toddler, aged 2 years, with Wolf-Hirschhorn syndrome characterized by generalized epilepsy within non-progressive epileptic encephalopathy (with slow wave EEG dysfunction) [23, 24]. The patient was receiving antiepileptic medication sodium-valproate.

The second subject was a male adolescent; aged 16 years, with complex partial epilepsy, receiving levetiracetam as antiepileptic medication.

For both subjects, an informed consent was provided by their parents.

### A. Sonification algorithm

Standard video-EEG recording was obtained using clinical EEG apparatus (NicoletOne, Sampling rate 500 Hz, Notch filter 50 Hz) and 10–20 electrode system placements [17].

The first subject had a slow basic activity in theta band (5-6 Hz) with multiple bilateral slow wave epileptic bursts (2.5 Hz), while the second subject had a regular alpha band basic activity (10-11 Hz) with a single short bilateral epileptic paroxysm.

The basic step of the EEG processing procedure was the calculation of signal power within 4 characteristic EEG bands: theta, alpha, beta and gamma. The calculation was done using 128 samples wide moving window function, which makes it suitable for the real-time implementation (0.32 s delay). Two frontal differential channels (Fp2-F4 and Fp1-F3) for the right and left sound outputs were selected. Changes in EEG data were the most prominent in selected channels.

For the theta dysfunction observed in the first subject, a 20 second-sound equivalent was generated using the sonification algorithm and short training audio file named *theta_1* was created. For the epileptic paroxysm observed in the second subject, a 6 second sound equivalent was generated using the same algorithm and short training audio file named *paroxysm_2* was created.

To increase statistical relevance of the evaluation test, we repeated and randomly embedded labeled theta dysfunction and paroxysm event five times each within 10 minutes of the normal EEG recording from the second subject, while the rest of the signal remained unchanged including natural variations (short non significant single spikes and muscle activity artifacts). This hybrid test sound file was named *AUDIO*.

Translating the EEG into a sound was guided by two factors; dominant EEG features changes during detected epileptic paroxysm and theta dysfunction events and the harmony of sound output. Distinctive spectral features of both events were implemented as the key factor in sound synthesis algorithm. Comparing power portions inside different bands, we could discriminate not only "normal" from the paroxysm, but also intermediate states that are used to provide higher sensibility and transient feedback. The implementation of our algorithm during events was designed to result in increases in sound volume and a chord base frequency, but consequently, to increase the dynamics of the generated sound. The idea was to stress out important changes in EEG data. With the intention to have characteristic sound pattern during the event but also, relatively dynamic and harmonic sound while EEG is in "normal" range, we derived a method of generating chords related to log or relative spectral powers. Otherwise, as the EEG signal amplitude during "normal" periods is significantly lower than while paroxysm, it would result in constant chord that becomes very unpleasant in short period of time. The

EEG spectrogram and the output sound spectrogram are shown in Figure 1. The sonification algorithm is presented on Figure 2.

### *B. Sonification validation via survey*

Eighteen volunteers (39% males; mean age 28.2 ± 6.5 years; biomedical engineers, students of biomedical engineering and healthcare professionals) participated in a survey. They were instructed to listen to the training audio files: *theta_1* and *paroxysm_2* and then test the file *AUDIO*. During listening to the test file, they had to fill the scales and to determine which of the events it was (the theta dysfunction labeled as 1 or the epileptic paroxysm labeled as 2) and when they occur within *AUDIO* file. Finally, they were asked to rate the sound sample and to answer whether they would be able to listen to the test file in the background, while performing some other, usual activity.

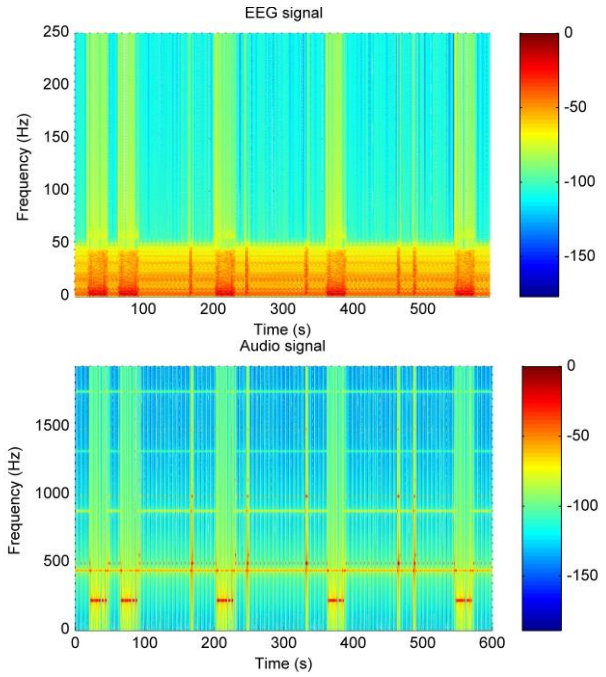


Fig. 1. The EEG spectrogram (upper picture) of 10 min and spectrogram of the corresponding single channel audio signal (lower picture). EEG recording with 10 times randomly inserted epileptic paroxysm (5 times slow wave dysfunction – wide vertical bars and 5 times paroxysm – narrow vertical bars). The time of slow wave dysfunction occurring was respectively: 20, 64, 202, 361, 545 s. The time of paroxysm occurring was respectively: 165, 245, 330, 462, 485 s.

## III. Results

In total, 54.4% of all events were detected accurately by our participants (Table 1). The *Theta_1* event was accurately registered by 77.8% of cases, while the *Paroxysm_2* event was accurately registered by 31.1%. The sensitivity of the method was 54.4% (true positive rate: TPR= TP/ (TP+FN)) and the precision was 38.4% (positive predictive value: PPV= TP/ (TP+FP)). The false discovery rate (FDR= 1 – PPV) was 0.62, while the false negative rate (FNR= 1 – TPR) was 0.46. During the survey, subjects didn't have to reject "false" changes in the sound sample, thus there were no true negative values (TN) and the specificity (SPC, true negative rate) was not calculated. The sample sound was marked between "unpleasant" and "pleasant".

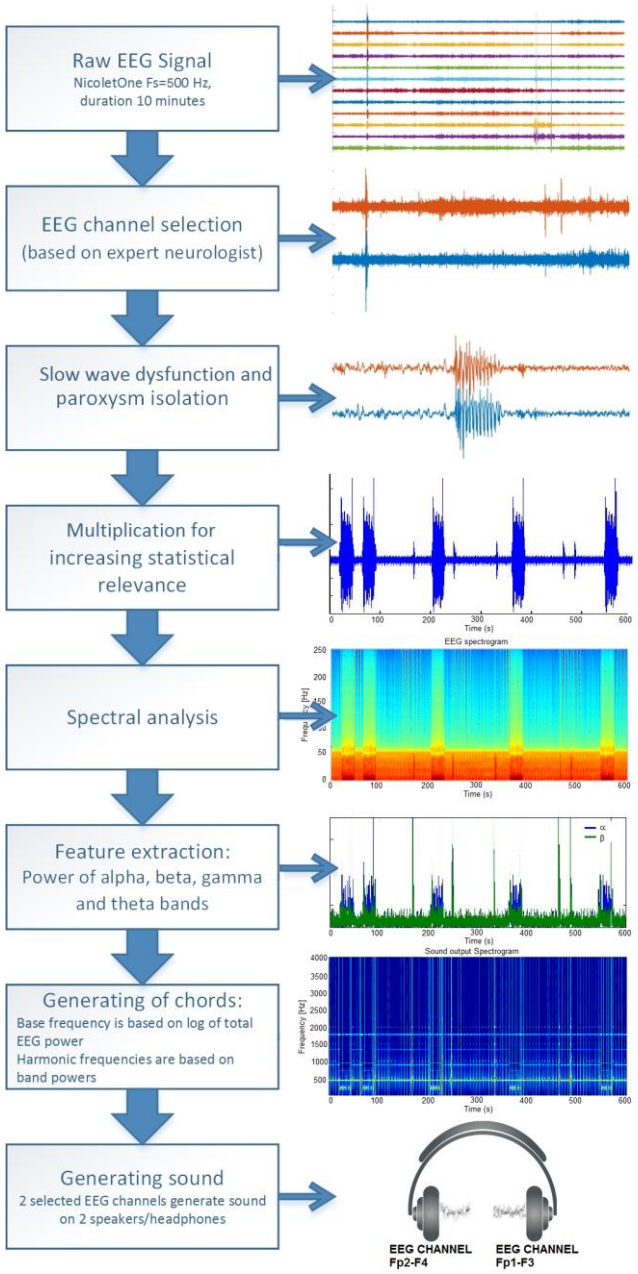


Fig. 2. Sonification algorithm which consists of 8 steps from recording of the EEG data to the generation of the sound sample.

TABLE I
SURVEY RESULTS REGARDING SONIFICATION ALGORITHM EFFECTIVENESS ASSESSMENT (MEAN ± SD [MIN])

| | |
|---|---|
| Average number of registered events in the sound sample | 14.2 ± 4.5 |
| Average number of accurately registered events (n=10) | 5.4 ± 3.1 |
| Average number of accurately registered *theta_1* event (n=5) | 3.9 ± 1.6 |
| Average number of accurately registered *paroxysm_2* event (n=5) | 1.6 ± 2.2 |
| The test sound average mark/description (0 – very unpleasant, 1 – unpleasant, 2 – pleasant, 3 – very pleasant) | 1.44 ± 0.6 (between unpleasant and pleasant) |
| Would subject be able to listen to the sound in background while performing some other activity (and how long)? | 2/3 would be able (from < 1 min. up to > 6 h) |

## IV. DISCUSSION

This paper presents further development and evaluation of the spectral analysis - parameter mapping sonification method which was earlier described [22].

Contrary to the previous research of De Campo [6], when was used a real time sonification method combined with EEG reader in population of EEG specialists – neurologists, or medical practitioner and neuroscientists according to Vialatte, [25], our resulting sound was evaluated mostly by non-neurologists and non-medical practitioners. The majority of sound raters in survey had no previous knowledge in the field of clinical encephalography. This makes our sound evaluation more objective regarding possible further implementation of this sonification method in non-hospital conditions and usage by non-medical users.

A similar study approach was used by Loui [21] where they have tested parameter mapping sonification algorithm on epileptic and non-epileptic EEG data in off-line conditions. After a short training, average hit rate of non-expert listeners was 63.5%. Our average hit rate was 77.8% for the theta dysfunction and 31.1% for the short paroxysm. In the mentioned study, listeners had only to choose whether the sound is "epileptic" or "non-epileptic", while in our study listeners had to differentiate between two "epileptic" sounds randomly occurring in a "non-epileptic" background.

The basic sound (representing non-epileptic EEG data from second subject) changed dynamically - predominantly with alpha band frequency oscillations. Major changes were randomly incorporated two sound events lasting approximately 20 and 6 seconds, respectively. In addition, numerous non-significant single spike discharges and artifacts in background EEG data changed the corresponding sound to some extent. This can explain why the second sound event (*paroxysm_2*) was under recognized. Namely, the second sound event was hard to differentiate from normal background sound oscillations, due to its short durance and similarity to short non-significant bursts in EEG, as opposite to the first sound event, which demarcated itself more profoundly regarding duration and frequency. In the study by Loui [21] only short (10 s) samples of normal EEG without bursts or artifacts were used to create "non-epileptic" sound. We used 10 minutes of EEG recording with all non-significant bursts and artifacts for "non-epileptic" sound. This makes our approach more realistic to clinical or home conditions.

Earlier studies implemented sonification methods in long-term EEG monitoring in hospital conditions (e.g. intensive care unit with two channel low resolution EEG recording) [2, 5]. Our method is not suitable for long term surveillance due to its low sensitivity (54.4%) and low precision (38.4%), thus it needs further assessments

## V. CONCLUSION

Preliminary from this study, it is possible to convert pathologic EEG data into an acceptable sound using the parameter mapping sonification method. This real time method could be used in clinical or home conditions for slow wave dysfunction detection. It demarks longer events with grater differences in frequency spectrum compared to background activity. It needs further tuning-up and evaluation in many other types of epilepsy.


## ACKNOWLEDGMENT

This study was financially supported in part by the Serbian Ministry of Education, Science, and Technological Development under Grant No.175016.


## REFERENCES


[1] T. Hermann, P. Meinicke, H. Bekel., H. H. Müller, S. Weiss, R. Helge, „Sonifications for EEG data analysis," Proc. ICAD'02, Kyoto, Japan, pp. 1-5, July 2-5, 2002.

[2] E. Adrian and B. Matthews, "The Berger rhythm: potential changes from the occipital lobes in man," *Brain*, vol. 57, no. 1, pp. 355–385, Jan. 1934.

[3] G. Kramer, B. Walker, T. Bonebright, P. Cook, J. Flowers, N. Miner, and E. Al., "Sonification report: Status of the field and research agenda," National Science Foundation, Santa Fe, NM, Tech. Rep., 1999.

[4] A. Väljamäe, T. Steffert, S. Holland, X. Marimon, R. Benitez, S. Mealla, A. Oliveira, S. Jordà, "A review of real-time EEG sonification research," Proc. ICAD 2013, Lodz, Poland, July 6-10, 2013. ISBN 8372835462, 9788372835468.

[5] A. Temko, W. Marnane, G. Boylan, J.M. O'Toole, G. Lightbody," Neonatal EEG audification for seizure detection," Proc. IEEE Eng Med Biol Soc, Chicago, Illinois, USA, pp. 4451-4454, Aug. 26-30, 2014.

[6] A. De Campo, "A data sonification design space map," Proc. ISon'07, York, UK, pp. 1-4, February 3, 2007.

[7] G. Baier, T. Hermann, U. Stephani, "Event-based sonification of EEG rhythms in real time," *Clinical Neurophysiology*, vol. 118, no. 6, pp. 1377-1386, 2007.

[8] T. Hermann, G. Baier, U. Stephani, H. Ritter, "Vocal sonification of pathologic EEG features," Proc. ICAD 2006, London, UK, pp. 158 – 163, June 20-23, 2006.

[9] T. Hermann, G. Baier, U. Stephani, H. Ritter, "Kernel regression mapping for vocal EEG sonification," Proc. ICAD 2008, Paris, France, pp. 1-7, June 24-27, 2008.
[10] E. R. Miranda and A. Brouse, "Interfacing the Brain Directly with Musical Systems: On Developing Systems for Making Music with Brain Signals," *Leonardo Music Journal*, vol. 38, no. 4, pp. 331–336, 2005.
[11] D. F. Weaver and B. Pohlmann-Eden, "Pharmacoresistant epilepsy: Unmet needs in solving the puzzle(s)," *Epilepsia*, vol. 54, no. 2, pp. 80–85, 2013. doi: 10.1111/epi.12191
[12] R. S. Fisher, C. Acevedo, A. Arzimanoglou, A. Bogacz, J. H. Cross, C. E. Elger et al, "A practical clinical definition of epilepsy," *Epilepsia*, vol. 55, no. 4, pp. 475–482, 2014. doi: 10.1111/epi.12550
[13] T. Glauser, S. Shinnar, D. Gloss, B. Alldredge, R. Arya, J. Bainbridge et. al, „Evidence-Based Guideline: Treatment of Convulsive Status Epilepticus in Children and Adults: Report of the Guideline Committee of the American Epilepsy Society," *Epilepsy Currents*, vol. 16, no. 1, pp. 48–61, Jan/Feb, 2016.
[14] O. Devinsky, D. C. Hesdorffer, D. J. Thurman, S. Lhatoo, G. Richerson, "Sudden unexpected death in epilepsy: epidemiology, mechanisms, and prevention," *Lancet Neurol*, vol. 15, no. 10, pp. 1075-88, Sep, 2016. doi: 10.1016/S1474-4422(16)30158-2.
[15] S. R. Sinha, L. Sullivan, D. Sabau, D. San-Juan, K. E. Dombrowski, J. J. Halford, et al, "American Clinical Neurophysiology Society Guideline 1: Minimum Technical Requirements for Performing Clinical Electroencephalography," *J Clin Neurophysiol*, vol. 33, pp. 303–307, 2016. DOI 10.1097/WNP.0000000000000308
[16] Ž. Martinović, *Clinical electroencephalography*, 5th ed, Belgrade, Serbia, Naučna KMD, 2009. (in Serbian language)
[17] J. N. Acharya, A. J. Hani, P. D. Thirumala, T. N. Tsuchida, "American Clinical Neurophysiology Society Guideline 3: A Proposal for Standard Montages to Be Used in Clinical EEG," *J Clin Neurophysiol*, vol. 33, pp. 312–316, 2016.
[18] P. C. Gilmore, R. P. Brenner, "Correlation of EEG, computerized tomography, and clinical findings. Study of 100 patients with focal delta activity," *Arch Neurol*, vol. 38, no. 6, pp. 371-2, 1981.
[19] D. W. Marshall, R. L. Brey, M. W. Morse, "Focal and/or lateralized polymorphic delta activity. Association with either 'normal' or 'nonfocal' computed tomographic scans," *Arch Neurol*, vol. 45, no. 1, pp. 33-5, Jan, 1988.
[20] J. D. Geyer, E. Bilir, R. E. Faught, R. Kuzniecky, F. Gilliam, "Significance of interictal temporal lobe delta activity for localization of the primary epileptogenic region," Neurology, vol. 52, no. 1, pp. 202-5, Jan, 1999.
[21] P. Loui, M. Koplin-Green, M. Frick, M. Massone, "Rapidly learned identification of epileptic seizures from sonified EEG," Frontiers in human neuroscience, vol. 8, article 820, 2014.
[22] N. Malešević, J. Ćertić, B. Valčić, M. M. Janković, "Human brainwave sonification based on data modulation," Proc. 3rd IcETRAN, Zlatibor, Serbia, June 13 – 16, 2016, ISBN 978-86-7466-618-0T.
[23] A. Battaglia, J. C. Carey, S. T. South, "Wolf–Hirschhorn syndrome: A review and update," *Am J Med Genet Part C Semin Med Genet* , vol. 169, no. C, pp. 216–223, 2015.
[24] A. Battaglia, T. Fillipi, S. T. South, J. C. Carey, "Spectrum of epilepsy and electroencephalogram patterns in Wolf–Hirschhorn syndrome: experience with 87 patients," Developmental *Medicine & Child Neurology*, vol. 51, pp. 373–380, 2009.
[25] F. B. Vialatte, J. Dauwels, T. Musha, A. Cichocki, "Audio representations of multi-channel EEG: a new tool for diagnosis of brain disorders," *Am J Neurodegener Dis*; vol. 1, no. 3, pp. 292-304, 2012.