A SPATIAL AUDIO FREQUENCY MODULATION TECHNIQUE FOR SONIFICATION OF EPILEPSY-RELATED DISCHARGES

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1. ABSTRACT

Identification of interictal epileptiform discharges (IEDs) is an important task in the diagnosis of epilepsy, especially in the absence of recorded seizure activity. This identification is primarily done through visual analysis of electroencephalogram (EEG) recordings, which remains a time-consuming task for neurologists to complete. As such, sonification may present new solutions in the form of an adjunct or novel IED identification technique. To demonstrate this potential, this paper presents a spatially-distributed frequency-modulation sonification suitable for dynamic binaural listening over headphones. EEG data is sonified through frequency modulation, and IED artefacts from each EEG electrode are distributed spatially within a 3D soundfield presented for binaural auditory display. Each electrode's physical location on the scalp corresponds to a virtual location in the virtual 3D soundfield.

The research adopted an iterative design approach utilizing fast tinkering. Sonification techniques were then evaluated via user trials. This paper reports on the iterative development stage together with results from the project evaluation trial data. User participant trials were undertaken (*N*=31) and results indicate that participants with little to no EEG experience can identify IEDs by ear with some precision, however visual inspection is still more effective than auditory.

2. INTRODUCTION

Interictal epileptiform discharges (IEDs) are collection of patterns of EEG activity common in people with epilepsy. IEDs generally take the form of an abrupt change in polarity, resulting in a sharp contour or spikiness [1]. These spikes may recur rapidly in what is known as a polyspike rhythm, or be followed by an aftergoing slow wave [2]. The identification and analysis of these discharges is very important for epilepsy diagnosis [3]. Additionally, the types and frequency of IEDs are of central interest in applications such as seizure prediction [4].

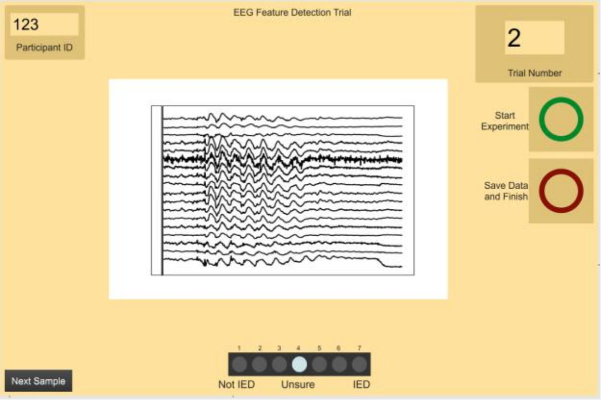
The identification of IEDs is mostly done by expert neurologists through visual inspection of EEG records [5]. This is time-consuming and has issues with reliability, although experts can generally agree with each other on the presence of IEDs [6]. In recent years interest has grown in novel approaches towards IED identification, mostly in the field of machine learning. However the most effective machine learning strategies still involve expert analysis as an adjunct [7].

Sonification, the perceptualisation of data as non-speech audio, has been used effectively in a number of fields including EEG analysis. In 2013, Väljamäe et al. reviewed a number of real-time EEG sonifications and found a breadth of applications in music, neurofeedback, brain-computer interfaces, neonatal EEG analysis and seizure detection [8].

Spatial audio is the production or recording of sound with a spatial component, allowing for the creation of immersive 3-dimensional soundfields, or for the simulation of individual sounds to appear to come from arbitrary directions. Nasir's 2007 review of the use of spatial audio in sonification concluded that it was a useful technique that was not fully utilised [9]. Dubus and Bresin's 2013 review of mapping strategies in sonification lists several studies using spatialization in sonification [10], however it does not distinguish between simple stereo panning (such as mapping two signals to two earphones) and more complex spatial audio techniques. More recent studies have used spatial audio for sonification of fMRI data, or for audio navigation tools for the blind and visually impaired [11, 12].

Research into the sonification of IEDs specifically is limited. In 2006, Baier et al. produced a sonification and demonstrated some examples of its use on interictal epileptic activity [13]. However no quantitative analysis has been made to evaluate its use as a diagnostic tool. In 2009 Wu et al. developed a sonification that primarily was aimed at identifying stages of sleep, but additionally mentioned its utility for identifying some types of IED [14]. Its accuracy for IED detection was not evaluated in that study, nor in any subsequent study by those authors.

In summation, prior research into the sonification of epileptic EEG has primarily focused on ictal (seizure) behavior and much less on the identification of interictal discharges. The existing research that does mention IED sonification is not focused on developing or evaluating usable tools for IED identification. Spatial audio is an underutilized technique with great potential for improving a sonification's effectiveness. As such, the development and evaluation of a spatial audio sonification of EEG data is warranted, with the goal of producing a sonification tool to aid in identifying IEDs.



123
Participant ID

2
Trial Number

Figure 1: The user interface of the testing software, showing a visual stimulus in the centre.

3. METHODOLOGY

3.1. Sonification

Thirteen EEG recordings were sourced from the Temple University Hospital EEG Corpus, a widely-used source of public-domain medical data [15]. These recordings, summing to approximately 10 hours in total, were analysed by expert neurologists from the Alfred Hospital in Melbourne. All IEDs present were identified and marked. These recordings served as the base data for sonification development.

The sonification developed for this study was a frequency-modulation technique, where the EEG voltage from each channel was mapped to the frequency of a sine wave. EEG data was imported from .EDF files and was split into individual channels. For each channel the electrode voltage was put through a lowpass filter at 100 Hz and a notch filter at 50 Hz to remove high-frequency noise and mains electricity interference. The filtered EEG voltage was scaled to the range of 1000-2000 Hz, then the sonification program generated a sine wave which varied frequency over time in step with the filtered EEG voltage. This caused IEDs and other EEG features to be recognizable as specific patterns in the pitch of a continuous tone. FM sonification is a very common mapping used in a variety of sonification applications.

As EEG recordings are almost always multi-channel, a spatial sound approach was used to help distinguish between channels. A collection of head related transfer functions were acquired from the open-source CIPIC HRTF database [16], and the positions of EEG electrodes on the scalp were calculated in spherical coordinates and used to convolve each channel with the corresponding HRTF. For instance the CZ electrode, positioned at the top of the head, corresponds to a sound coming from directly above the listener. Additionally, a time delay was calculated based on the speed of sound, and used to offset the left and right output channels to simulate an interaural time difference. These methods served to spatially distinguish between the channels, which otherwise tended to blend into one another. This technique is similar to a sonification by Mathew et al in 2017, though here the data modulates a generated sine wave rather than a looping audio track [17].

3.2. Experimental Trial

Participants were sourced through advertisements on posters around Swinburne University's campus, as well as through Swinburne University's Research Experience Program. 11 volunteer participants were recruited, 7 male and 4 female, aged between 19 and 67 years old. All participants did not use hearing aids and had no significant hearing loss, as confirmed by an audiometry hearing test performed immediately before the experiment. Participants generally had very little prior knowledge of EEG and epilepsy. All procedures were carried out in accordance with Swinburne University's ethics guidelines (ethics # 10253).

Prior to the experiment, 120 samples of EEG were selected from the annotated Temple University Hospital data, each 5 seconds in length. The samples were evenly divided in content, with 40 containing normal EEG, 40 containing IEDs, and 40 containing non-epileptiform transients and artifacts. All 120 samples were sonified with two variants of the sonification technique described in section 2.1, producing 120 audio samples per sonification variant. One variant used a one-to-one timescale, meaning the 5-second samples produced a 5-second audio file, while the other variant used a two-to-one timescale where a 5-second sample produced a 2.5-second audio file. Additionally, a visual stimulus was generated by making a simple unmarked graph of EEG voltages. Participants were randomly assigned to one sonification variant and one stimulus type: either audio-only, visual-only or both audio and visual stimuli.

Testing software was developed in MAX/MSP, to present participants with stimuli and record their responses. The program was set to a certain sonification variant and stimulus type, and would present the pre-recorded stimuli in a random order. After seeing or hearing each stimulus, participants were prompted to click on a confidence scale to record their belief of whether an IED was present in the sample. After recording their response, the software displayed the actual content of the sample, allowing the participant to learn to identify the EEG as they progressed through the experiment. This methodology was based on the methodology of Loui et al in 2014, although here the training was incorporated into the testing rather than separate [18].

After the software recorded the participant's response it presented another EEG sample, and repeated until the participant had responded to all 120 samples. The accuracy and confidence of each response, as well as the time taken to respond, was recorded for analysis.

4. RESULTS

The 31 participants produced 3721 responses in total, distributed as shown in Table 1. 'Unsure' responses, from the midpoint of the confidence scale, were counted as incorrect.

Overall, 72.2% of participant responses correctly stated the presence or absence of an IED. More confident responses also tended to be more correct, with 87.5% of high-confidence responses being correct compared to 62.8% of low-confidence responses. A Pearson's Chi-square test found the distributions of correctness for different confidence values were significantly different (p<0.001).

Table 2: Sensitivity and Specificity of Responses

Stimulus	Sensitivity	Specificity
Audio only x1	0.608	0.760
Audio only x2	0.702	0.729
Audiovisual x1	0.757	0.715
Audiovisual x2	0.703	0.706
Visual only	0.679	0.777
Total	0.689	0.739

The sensitivity and specificity of responses varied slightly between the different stimulus types, as shown in Table 2. Participants who received audiovisual stimuli had the highest sensitivity but lowest specificity, indicating that they were more likely to categorize a sample as an IED.

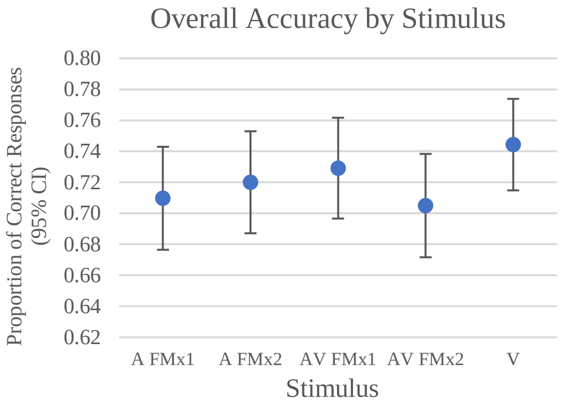


Figure 2: An error-bar plot of the proportions of correct responses varying between the different stimulus types. 'A FMx1' stands for audio-only stimuli at 1x speed, 'AV FMx2' stands for audiovisual stimuli at 2x speed, 'V' stands for visual-only stimuli.

The mean accuracy for each type of stimulus is shown in Figure 2. Notably, visual-only participants appear to have a higher overall accuracy than audio-only However, a one-way ANOVA found no significant difference in mean accuracy between stimulus types (F=0.97, p=0.42).

As the correctness of responses was clearly related to confidence, a variable was defined by taking the confidence of each response and multiplying by -1 if the response was incorrect. This 'response value' ranged from 3 to -3, with high values corresponding to high-confidence correct responses and low values corresponding to high-confidence incorrect responses. This helped to combine the two variables into one, for easier analysis.

Table 1: Crosstabulation of Response Confidence vs. Correctness

		Correct	Incorrect	Total
Confidence	0	0	260	260
	1	592	351	943
	2	633	213	846
	3	1463	209	1672
Total		2688	1043	3721

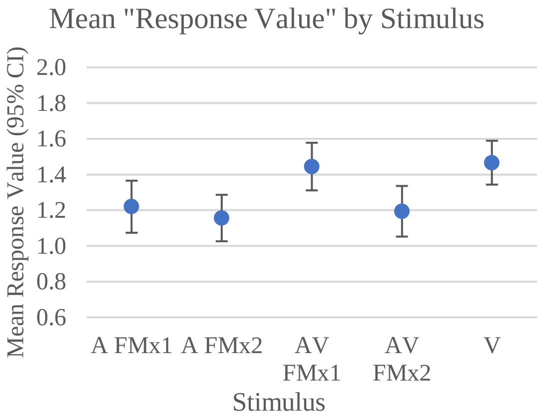


Figure 3: Error-bar plot of the mean calculated 'response value', varying between stimulus types.

A comparison of this 'response value' shows noticeable differences in its distribution between the different stimulus types, as depicted in Figure 3. Participants responding to visual-only stimuli had a higher average response values, a mean of 1.47 as compared to the audio-only mean of 1.19. A one-way ANOVA found a significant difference between stimulus types (F=4.71, p=0.001). Notably the two variants of audiovisual stimuli produced very different results, but the two audio-only variants were similar.

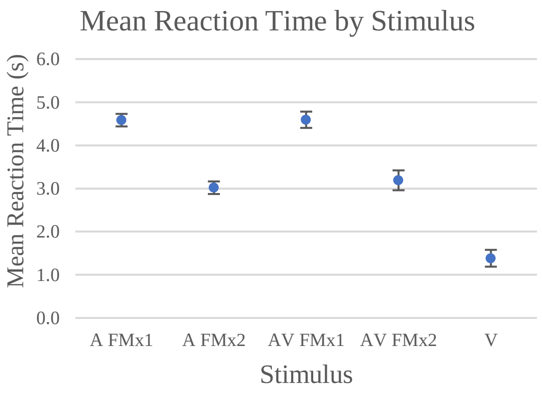


Figure 4: An error-bar plot showing the mean 'reaction time' for all stimulus types.

A naïve comparison of response times between the two sonification variants would not be an accurate measure, as the faster-playing sonification variant allowed participants to hear the IED (or lack thereof) earlier. As such a 'reaction time' variable was calculated for each audio stimulus, as an accurate measure of the real time from the beginning of the EEG feature in the audio sample to the participant recording a response. Figure 4 shows the mean 'reaction time', comparing the stimulus types. Participants clearly responded to the 2x speed sonification variant much faster than they did to the 1x speed variant, and visual-only participants responded fastest of all. A one-way ANOVA found significant differences between the means of different stimulus types (F=210, p<0.001).

5. DISCUSSION

The overall accuracy of participants' responses was good, indicating that the simple FM sonification allowed novices to identify IEDs in sonified audio with decent sensitivity and specificity. However, the visual-only stimulus method was unexpectedly more effective than the other stimuli, even compared to audiovisual stimuli which augmented the visual stimulus with sonified audio. This contrasts with comments from participants after the experiment, many of whom stated that they felt the audio was easier to interpret.

The data also indicates that the sonification variant with a faster timescale allowed faster interpretation of IEDs, even after taking into account the participant's reaction time. However the faster variant also lowered the accuracy of responses. Further research may seek to evaluate sonification variants with an even faster timescale.

The effect of spatial sound on the sonification appears to be generally positive, as multiple participants reported that the effect was beneficial for understanding the sonification. Further research will use this methodology to compare the sonification technique to a variant with no spatial sound effects, for a quantitative analysis of its effectiveness.

A major limitation of this study is the choice of data for producing stimuli: the specific EEG samples chosen for sonification and visualization. The chosen samples had obvious differences between categories, such that normal EEG, artifacts, and IEDs were very easy to tell apart. This contributed to a large number of high-confidence 'not IED' responses, which may have skewed the data. Future studies might avoid this by choosing EEG samples such that IEDs are compared with IED-like artifacts, rather than entirely unrelated EEG phenomena.

6. CONCLUSION

This study evaluates the potential of a sonification technique for analysis of interictal EEG. The sonification technique uses binaural synthesis to spatially distribute EEG data into a soundfield surrounding the listener's head. The data was sonified through frequency modulation to produce separate audio tracks for each EEG electrode, then each track was spatialized to the virtual location of its corresponding electrode on the scalp.

An experimental analysis of the sonification was undertaken, and results show that non-expert listeners could quickly and accurately identify IEDs by ear alone, but were even faster and more accurate when relying only on visual data.

The utility of this FM sonification technique for the identification of IEDs appears limited, however the methodology may be used as a framework for evaluation of the utility of other sonification techniques.

7. ACKNOWLEDGMENT

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