ELECTROENCEPHALOGRAM STEADY STATE RESPONSE SONIFICATION FOCUSED ON THE SPATIAL AND TEMPORAL PROPERTIES

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ABSTRACT

This paper describes a sonification approach of multichannel electroencephalogram (EEG) steady-state responses (SSR). The main purpose of this study is to investigate the possibility of sonification as an analytic tool for SSR. The proposed sonification approach aims to observe the spatial property (i.e. location of strong brain activities) and temporal property (i.e. synchrony of wave forms across channels) of brain activity. We expect to obtain useful information on brain activity locations and their dynamic transitions by taking advantage of spatial sound with multichannel loudspeakers that represent EEG measurement positions, while expressing the temporal property of multiple EEG channels with timbre by integrating respective auditory streams. Our final sonification evaluation experiment suggests the validity of the proposed approach.

1. INTRODUCTION

We report a sonification of auditory-evoked steady-state responses (ASSR). ASSR is a type of the steady-state brain responses (SSR) [1]. Most of the previously proposed studies with electroencephalogram (EEG) data sonification aim for a clinical medicine application, such as diagnosing or comprehending the abnormal cerebral function, which occurs in epilepsy [2-6]. In this study, we investigate EEG sonification of more commonly observed brain activity phenomenon, such as SSR. This study extends the sonification of SSR [7-9] with better expression of data properties.

Unlike epilepsy, SSR is observed among many healthy people. SSR is a brain activity phenomenon such that when a periodic stimulation is presented, EEG signals show a periodic pattern of the exact same frequency at many parts of the brain. While the most significant application of ASSR is the screening test for newborn's hearing, developing brain-computer interface (BCI) using ASSR is also regarded as promising [10].

The mechanism of SSR is still under investigation. However, in general, a response to an external stimuli occurs from a certain location and that response eventually propagates to all over the brain: For example, when an auditory stimulus is presented, its initial response starts on auditory pathway and quickly propagates to the other parts of the brain [11]. Taking arithmetic mean of multiple EEG measurements is a typical way to detect SSR, but in order to understand the mechanism of SSR, observing subtle changes from single-trial data is expectedly more effective. With this goal, we propose a sonification method for single-trial SSR data that can represent the location and the temporal transition of brain activity.

In order to analyze the mechanism of SSR, we focus on the spatial property (i.e. location of strong brain activities) and the temporal property (i.e. synchrony of wave forms across channels), so that we could understand where and when the SSR start and propagate in the brain. To represent the spatial property, we map the spatial arrangement of the brain activity to the sound spatialization, using a multi-channel, three-dimensional loudspeaker setting.

Moreover, to represent the temporal property of data, we map the temporal patterns of data onto the temporal pattern of the synthesized sounds (i.e. patterns of onset, sustain, modulation, and decay). Because of the auditory streaming effect, the sounds of a similar temporal pattern fuse together, and the sounds of different temporal patterns segregate each other [12]. The synchrony across multiple data channel (i.e. data sharing a same temporal pattern across channels) can be perceived as the fusion of sounds with a composite timbre.

Detection of neural responses (including SSR) usually requires repeated measurements and detailed statistical analysis, taking long time to unveil the interesting features in the neural activities. We expect this sonification method provides a flexible framework for single-trial EEG data analysis for both experimenter and subject. Such a framework will help the development of the real-time data analysis and the applications such as auditory biofeedback and auditory BCI.

2. EEG STEADY STATE RESPONSE SONIFICATION METHOD FOCUSED ON THE SPATIAL AND TEMPORAL PROPERTY

This work focuses on the "synchrony" property of SSR such that a response occurs in the same frequency band as a stimulus frequency. We propose a sonification method using the amplitude change of a frequency bin in a power spectrum corresponding to the stimulus frequency. Fig. 1 shows the proposed framework. First, we conduct short-time Fourier transform (STFT) for input EEG data, and then we extract the spectral information corresponding to the stimulus frequency. Then we normalize spectral amplitude to emphasize an interesting data property: we propose two normalization methods, one to focus on the spatial property, and another to focus on the temporal property. The transitions of the EEG signals are sonified as mixture of sounds with each of them corresponding to a single EEG channel: each component's sound can exhibit the transition from textured density to the tone-like quality of the timbre as the brain activity becomes stronger. And we employ three-dimensional sound as the sound reproduction environment. By associating timbre and the sound image position with EEG measurement position, the information of strength and location of brain activity can be obtained.

2.1. STFT and extracting stimulus frequency bin

First, we conduct STFT for input EEG data, and calculate the spectrogram by taking its power. Then we extract the spectral information corresponding to the stimulus frequency from calculated spectrogram, and we use its spectral amplitude as a parameter for the sound synthesis. By presenting only the information that is associated with the SSR, the proposed sonification method decreases the effort on users to recognize SSR. The power spectrum of the stimulus frequency bin (k_0) at the i^{th} EEG channel is obtained as follows:

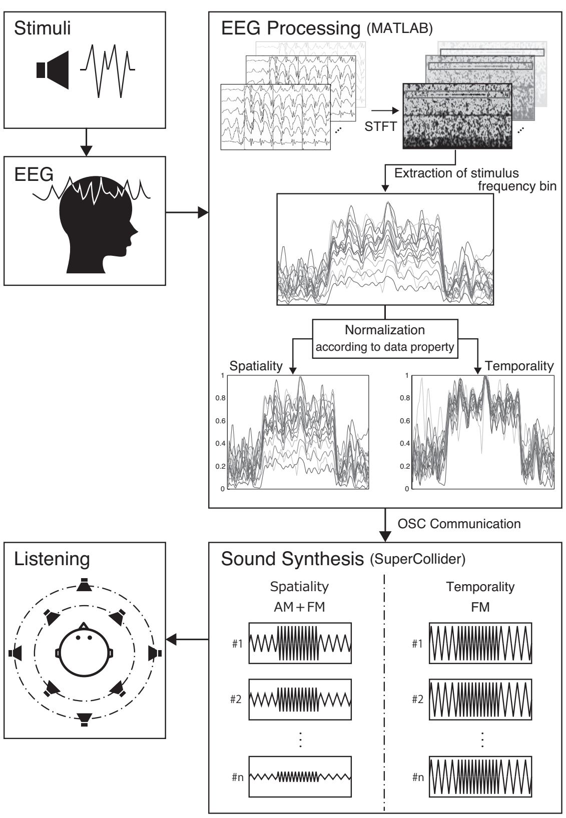


Figure 1: The framework of proposed SSR sonification method.

$$X_{i,k_0}[n] = \sum_{m=n-N+1}^{n} x_i[m] e^{-j\left(\frac{2\pi}{N}\right)k_0 m}, \tag{1}$$

where N is the window length (0.1 ms) of STFT and x_i is the i^{th} EEG channel signal.

2.2. Normalization according to data properties

The normalization is to deform data based on a certain rule to make it easier to use. In this study, we propose two normalization methods according to data properties, one to focus on the spatial property (normalization across EEG channels), and another to focus on the temporal property (normalization within EEG channel). We aim to make an interesting data property clear by normalizing spectral amplitude. In addition, since the value of spectral amplitude is limited to the range from 0 to 1, the association with sound synthesis parameter and data feature quantity is facilitated.

2.2.1. Normalization across EEG channels

The normalization across EEG channels is performed by dividing the power spectrum of each channel in the time domain using the maximum amplitude value of the stimulus frequency bin across EEG channels. The spectral value after the normalization is obtained as follows:

$$\tilde{X}_{a_i}[n] = X_{i,k_0}[n] / X_{\max}, \tag{2}$$

where X_{max} is the maximum amplitude value of the stimulus frequency bin across EEG channels. In this normalization, the power ratio across EEG channels is conserved and this relationship is reflected in the sound. Therefore, the user can focus on the spatial property of data and identify the EEG channel in which strong brain activity is happening.

2.2.2. Normalization within EEG channel

The normalization within EEG channel is performed by dividing the power spectrum of each channel in the time domain using the maximum amplitude value of the stimulus frequency bin in each EEG channel. The spectral value after the normalization is obtained as follows:

$$\tilde{X}_{w_i}[n] = X_{i,k_0}[n] / X_{i,\max}, \tag{3}$$

where $X_{i,,max}$ is the maximum amplitude value of the stimulus frequency bin at i^{th} EEG channel. In this normalization, it is possible to observe the time change of EEG signals regardless of the magnitude of spectral amplitude. Therefore, the user can focus on the temporal property of data and identify the synchrony pattern across EEG channels.

2.3. SOUND SYNTHESIS METHOD

Single-channel sonified sound is generated from single EEG channel data according to the sound synthesis method described below. For multichannel EEG data, the proposed method generates multichannel sonified sound according to the number of EEG channels and reproduces them respectively from multichannel loudspeakers associated with EEG measurement position. A user listens to the auditory stream that is spatially formed by these sounds.

2.3.1. Sonification focusing on the spatial property

In sonification focusing on the spatial property, the power spectrum value normalized across EEG channels is mapped to the amplitude of pulse wave and pulse period. Table 1 shows the relationship of the spectral value and sound synthesis parameters. A pulse wave has a characteristic that it is perceived as an interval “length” if pulse interval is long (low frequency), but on the other hand it is perceived as a "pitch" if pulse interval is short (high frequency). From such difference of the perception, we aim to perceive the occurrence of SSR and the intensity of brain activity intuitively.

Table 1. The mapping of sonification focusing on the spatial property.

EEG parameter	Sound Synthesis Parameter
Power spectral [0, 1]	Pulse frequency [10Hz, 400Hz] Gain [-20dB, 0dB]

2.3.1. Sonification focusing on the temporal property

In sonification focusing on the temporal property, the power spectrum normalized within the EEG channel is mapped to only the period of pulse wave. Table 2 shows the relationship of spectral value and sound synthesis parameter. It is possible to observe the time change of EEG signals regardless of the magnitude of spectral amplitude because of the constant sound volume. We aim to perceive the synchrony pattern and the propagation process of SSR.

Table 2. The mapping of sonification focusing on the temporal property.

EEG parameter	Sound Synthesis Parameter
Power spectral [0, 1]	Pulse frequency [80Hz, 400Hz]

3. EVALUATION TEST OF PROPOSED SONIFICATION METHOD

3.1. Dataset used for the sonification

In order to generate sonification sounds, we used single-trial EEG data of four persons that were measured under the conditions shown in Table 3 and 4. This dataset was acquired part of the study on ASSR [13]. The online EEG experiments were conducted in accordance with The World Medical Association Declaration of Helsinki - Ethical Principles for Medical Research Involving Human Subjects. The procedures for the EEG recordings were approved by the Ethical Committee of the Faculty of Engineering, Information and Systems at the University of Tsukuba, Tsukuba, Japan. The experimental protocol was explained in detail to the subjects who agreed voluntarily to participate by signing the consent forms. During the EEG recording, they were presented modulated sine waves as auditory stimuli for ASSR using headphones. The acquired EEG data consist of sixteen EEG channels according to the international 10-20 system [14].

3.2. Overview of the evaluation test

The evaluation test of the proposed sonification method was conducted in a studio at the University of Tsukuba, TARA Center. The procedures were approved by the Ethical Committee of the Faculty of Engineering, Information and Systems at the University of Tsukuba, Tsukuba, Japan. We conducted two types of experiments to evaluate the proposed sonification method: The first task is to identify the location of strong brain activity; the second task is to rate the strength of synchronization across EEG channels. Subjects who participated in the first task were 15 people (4 females and 11 males, average age being 23.6 years old), and subjects who participated in the second task were 15 people (3 females and 12 males of the early 20s). They were all healthy people with no clinical history related to speech and hearing.

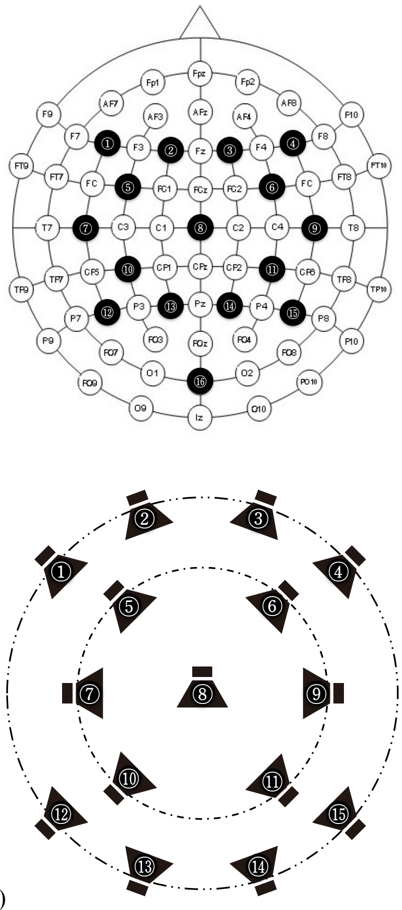
Fig. 2 shows the association between EEG measurement positions and the arrangement of loudspeakers. We present sonified sound with 15 channel loudspeakers associated with EEG measurement position to obtain useful information on brain activity locations. The signal measured by the electrode on ‘POz’ is not used for sonification because of the limited number of playback channels. The loudspeakers were set in two levels: eight at the middle level (about the height of the listener’s ear) and the ceiling level. The listener sat in the center of the room and was able to turn the head, but not allowed to stand up or walk around.

Table 3. EEG recording conditions.

Number of subjects	4
EEG amplifier	g.USBamp with g.SAHARA dry active electrodes
Electrode arrangement	F5, F1, F2, F6, FC3, FC4, C5, Cz, C6, CP3, CP4, P5, P1, P2, P6, POz
Sampling frequency	512 Hz
Stimuli	Modulated tone of a sine wave
Stimulus presentation time	10 sec

Table 4. The number of trials for one subject

Types of modulated tone		Number of trials
Carrier frequency [Hz]	Modulated frequency [Hz]	
500	40	10
500	77	10
1000	40	10
1000	80	10



(a)

(b)

Figure 2: The association between loudspeakers and EEG measurement positions. (a) shows 16 EEG measurement positions. (b) shows the arrangement of 15 loudspeakers associated with EEG measurement position (the outer circle corresponds the middle height, and the inner circle and the center speaker is at the ceiling height.)

3.3. Identification experiment of the spatial localization of brain activity

In the identification experiment of the spatial localization, we use the sonification focusing on the spatial property. The purpose of the experiment is to examine whether subjects can identify the presence of localization and the localization channel. Here, “localization” means that the strong brain activity appears in a particular location. Experimental task is carried out in two stages of "Identification of the presence of localization" and " Identification of the localization channel". We examine the effectiveness of the sonification focusing on the spatial property by comparing the chance level and correct answer rate of the task.

3.3.1. Experimental method

<u>*Task Ⅰ: Identification of the presence of localization*</u>

We first analyzed the strength of the localization patterns using RMSE (Root Mean Square Error) of the power at stimulus frequency bin across EEG channels, and selected 30 data to be sonified: 15 data with strongest localization patterns and 15 data with weakest localization patterns. We then synthesized 30 sounds with the dataset, and presented them to our listeners in a random order. Listeners evaluated the presence or absence of localization. We finally determined if the listeners judgments were correct or not, by comparing them with our analysis of strong/weak localization patterns.

<u>*Task Ⅱ: Identification of the localization channel*</u>

For this task, we used the same 15 data with strongest localization patterns from the task I, although the sound playback locations of the EEG channels were shuffled. The sonified sounds of the 15 data were presented to the listeners in a random order. Listeners judged the location where the strongest brain activity happens, and answered speaker locations from which outstanding sound was heard. Since the original signal may have contained multiple channels that exhibit similarly strong power level, the listeners were allowed to answer up to two outstanding locations. We then determined if the listeners answered the speaker channel that corresponded to the EEG channel with the strongest activity.

3.3.2. Experimental results

<u>*Task Ⅰ: Identification of the presence of localization*</u>

Fig. 3 shows the accuracy rate in Task Ⅰ. Subjects identified the presence or absence of localization at 77% accuracy on average, ranging from 50% to 97%. The average correct answer rate of all subjects including 95% confidence intervals exceeded the chance level (50%). Therefore the sonification focusing on spatial property is capable of determining the presence or absence of localization.

<u>*Task Ⅱ: Identification of the localization channel*</u>

Fig. 4 shows the accuracy rate in Task Ⅱ. Subjects identified the localization channel at 88% accuracy on average, ranging from 53% to 100%. The average correct answer rate of all subjects including 95% confidence intervals exceeded the chance level (13%). Therefore the sonification focusing on spatial property is capable of determining the location where the strongest brain activity happens.

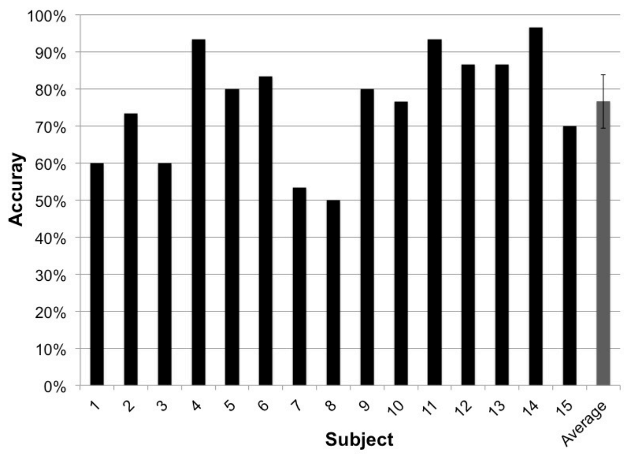


Figure 3: The accuracy rate in Task Ⅰ.

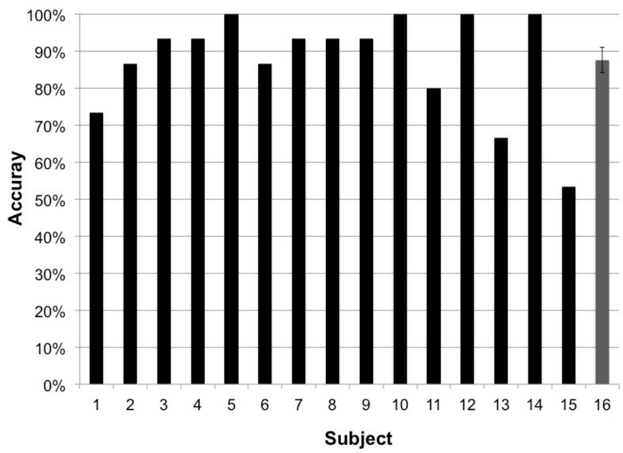


Figure 4: The accuracy rate in Task Ⅱ.

Furthermore, we analyzed the cases where a subject answered two channels. In these cases, we defined that the answer is correct if the RMS of the power at the corresponding EEG channel is ranked within the top three of the powers from all the channels. The percentage of answers with two channels in the task II is 33 % for all the trials. Fig. 5 shows the rate of (1) either one of the two answered channels being correct, (2) both of the answered channels being correct, and (3) both of the answered channels being incorrect. The rate of both correct answers was 85% on average, meaning that subjects could determine multiple outstanding channels at once. Therefore the listeners were capable of determining multiple locations where strong brain activities happened, with the sonification focusing on spatial property.

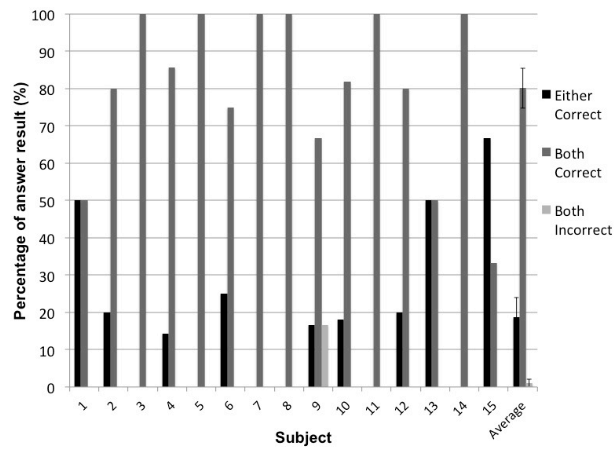


Figure 5: The analysis of the cases where a subject answered two channels in Task Ⅱ.

3.4. Pairwise comparison experiment of the strength of synchronization across EEG channels

In the paired comparison experiment of the strength of synchronization across EEG channels, we use the sonification focusing on the temporal property. The purpose of the experiment is to examine whether subjects can assess the degree of synchronization across EEG channels. In this experiment, subject listens a pair of sonified sound and judges the dissimilarity of the perceived strength of synchronization across EEG channels between two sounds. We examine the effectiveness of the sonification focusing on the temporal property by comparing the average correlation coefficient across EEG channels and the estimate of the judgment obtained from the experiment.

3.4.1. Experimental method

Table 5 shows the three dataset for this experiment. Dataset A, B, and C hold low, middle, and high RMS values, respectively. Each set consists of four data with gradually increasing correlation coefficient while RMS values were fixed as much as possible. We select them based on the average value of the correlation coefficients across EEG channels and the average value of the RMS at stimulus frequency bin: the strong correlation across the EEG channels means that they share a similar temporal pattern, and the strong RMS value means the strong ASSR.

This experiment is based on Scheffe's pairwise comparison method [15]. Each dataset contains six pairs of sonified sound. Subjects listen to the pairs in a random order and judge the degree of synchronization across EEG channels with 5-point scale shown in Table 6.

3.4.1. Experimental results

Fig. 6-8 show the results of regression analyses from the subjective evaluation value and the correlation coefficient across EEG channels. The coefficient of determination R^2 is 0.88 on average for all dataset, that is, the result showed high reliability. Therefore the sonification focusing on temporal property is capable of determining the degree of synchronization across EEG channels.

Table 5. The dataset for identification experiment of the strength of synchronization across EEG channels.

Dataset	Average value of RMS	Average value of correlation coefficient
A	0.84	0.06
	0.81	0.28
	0.85	0.49
	0.87	0.71
B	1.12	0.22
	1.11	0.41
	1.12	0.61
	1.18	0.79
C	1.51	0.20
	1.63	0.34
	1.65	0.41
	1.64	0.64

Table 6. The 5-point scale of pairwise comparison

Category	Judgment
1	Earlier sound has a much stronger synchronization
2	Earlier sound has a slightly stronger synchronization
3	Both sounds have a similar level of synchronization
4	Later sound has a slightly stronger synchronization
5	Later sound has a much stronger synchronization

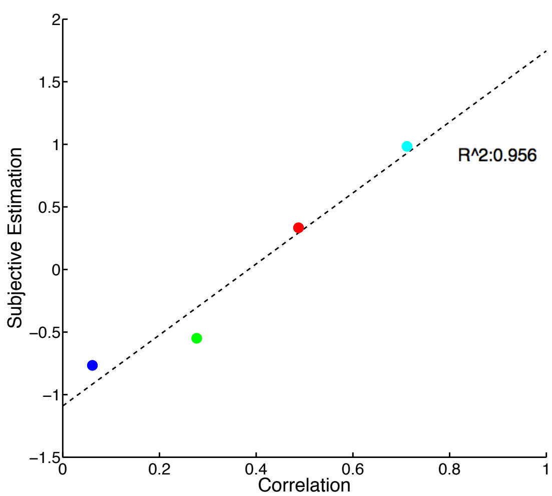


Figure 6: The result of regression analysis for dataset A.

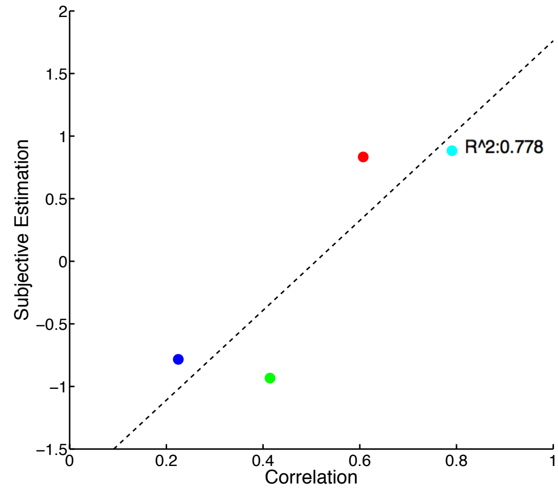


Figure 7: The result of regression analysis for dataset B.

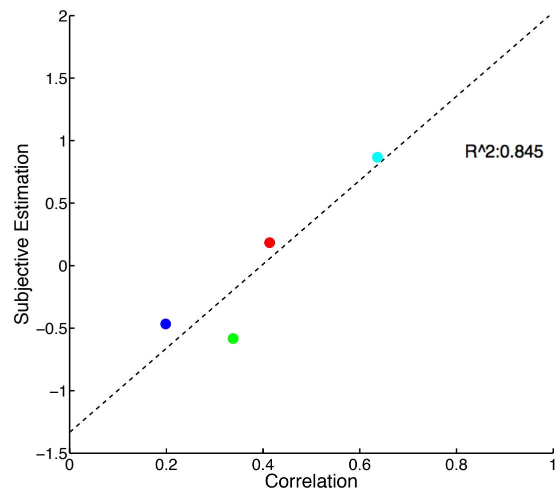


Figure 8: The result of regression analysis for dataset C.

4. CONCLUSIONS

We proposed a method of a multichannel EEG sonification that focused on the temporal and spatial characteristics of brain activity. The proposed method targets at the "synchrony" property of SSR such that a response occurs in the same frequency band as a stimulus frequency. From this property, the amplitude change of the stimulus frequency bin in a power spectrum was used for sonification. In addition, clarifying the data property to be focused by the normalization, we aimed to decrease the effort on users to understand the data. In this study, we proposed two normalization methods according to data properties, one to focus on the spatial property, and another to focus on the temporal property.

From the evaluation experiment, we found that listeners successfully identified the location where strong brain activity happened with the sonification focusing on the spatial property. With the sonification focusing on the temporal property, the subjective judgment of synchrony across EEG channels well matched with the correlation coefficient across EEG channels, suggesting that listeners can accurately assess the degree of synchronization across EEG channels with sonification. These results suggest that our attempt on sonifying the spatial and temporal properties can help observing such properties of single-trial EEG data. The future work of this research includes simultaneous evaluation of the spatial and temporal synchrony, and comparing analysis performances and user's effort (i.e. cognitive load on users) between proposed method and traditional visualization methods.

5. ACKNOWLEDGMENTS

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