EEG Steady State Synchrony Patterns Sonification

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***Abstract*—This paper describes an application of a multichannel EEG sonification approach. We present results obtained with a multichannel-sonification method tested with steady-state EEG responses. We elucidate brain synchrony patterns in an auditory domain with utilization of the EEG coherence measure. The transitions in the synchrony patterns are represented as timbre (i.e., spectro-temporal) deviation and as spatial movement of the sound cluster. Our final sonification evaluation experiment with six subjects confirms the validity of the proposed brain synchrony-elucidation approach.**

I. Introduction

Data sonification is a method of converting data into non-speech audio and to observe characteristics of the data through hearing [1], [2], [3]. Most of the previously proposed studies with EEG data sonification aim for a clinical medicine application, such as diagnosing or comprehending the abnormal cerebral function, which occurs in epilepsy [4], [5], [6], [7], [8].

In this study, we apply sonification to EEG steady-state responses (SSR) [9], which are often used in brain-computer interface (BCI) technologies [10]. 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 [9]. The mechanism of SSR is still not clear in neuroscience. The purpose of this study is to elucidate, using sonification, the process of an occurrence and propagation of SSR that is captured by scalp-surface EEG. In this report, we focus on the "synchrony" of SSR and propose the sonification method reflecting the degree of a spectral correlation between two EEG channels by using coherence analysis that represents the similarity between time-series data. Lastly, the sonification is evaluated by users in order to verify the effectiveness of the auditory representation of the coherence analysis.

II. Methods

In this paper we describe the EEG sonification method toward the understanding of EEG SSR coherence patterns.

Figure 1 shows our sonification framework. In the first stage, EEG coherence analysis is performed in MATLAB, using the pre-measured EEG signals that show the SSR. Using the OpenSound Control (OSC) protocol, the results of the EEG coherence analysis are transmitted from MATLAB to SuperCollider. With the SuperCollider software package, we performed the sonification of the coherence analysis, using the overtone mapping [11]. The final outcome is a four-channel surround audio representation of the EEG coherence values.

A. EEG Measurement Experimental Protocol

The EEG recordings for the proposed sonification experiments were conducted in the Laboratory for Adaptive Brain Signal Processing, RIKEN BSI, Japan. The experiments were designed and performed following the institutional ethical committee guidelines for experiments with human subjects. The experimental protocol was explained in detail to the subjects who voluntarily agreed to participate by signing consent forms. We performed the experiments using active EEG electrodes connecting to BIOSEMI activTWO amplifiers with electrodes connects at the $F1$, $F2$, $P1$, and $P2$ sites according to the international $10/10$ system. The sampling frequency was 2048 Hz.

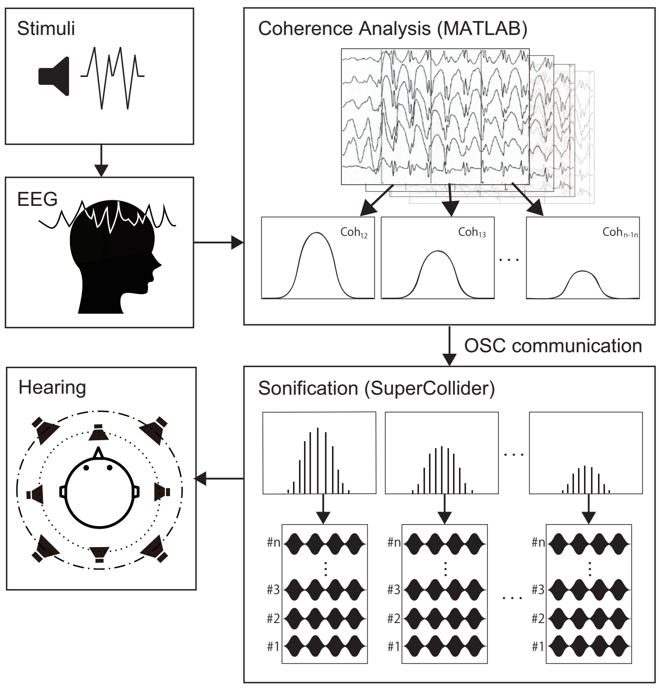

Fig. 1. The framework of EEG SSR sonification.

B. Steady-State Visual Potential Sonification Based on Pair-wise Electrode Coherence Analysis

As introduced earlier, the steady-state response is a periodic brain-activity pattern evoked by the presentation of periodic stimulation [9]. When visually flashing stimuli are used, the response is called a steady-state visually evoked potential (SSVEP), and is often applied for brain-computer interfaces (BCI). However, the mechanism of SSR is still not clear in neuroscience. Thus we aim at spatial sonification of the phenomenon to help scientists to elucidate it.

Coherence is a quantitative measure of the spectral consistency between two signals. The coherence measured between two EEG electrode signals provides a measure of mutual influence or "synchrony." The magnitudes of the estimated influences in complex, non-linear dynamic systems can be quite different at different frequencies or different spatial scales [12]. Therefore, sonification of pair wise coherence dynamics in multichannel EEG recordings with known steady-state responses can bring new value to spatial brain-activity analysis compared with classical spectral features [13]. The range of coherence value is from 0 to 1, and its value reflects the degree of spectral correlation. The paper by Kaminski [14] clearly indicated that using coherence for EEG data processing is effective in analyzing a correlation within the pairs of EEG channels.

Coherence is calculated with the auto-power spectral density (aPSD) and the cross-spectral density (cPSD) between two time series. The single i^{th} EEG channel signal $s_i(t)$ yields the complex Fourier transform $S_i(f)$. The aPSD for the channel i is obtained as follows:

$$G_i(f) = S_i(f)S_i^*(f), \qquad (1)$$

and the cPSD for a pair of channels i and j is:

$$G_{ij}(f) = S_i(f)S_j^*(f), \qquad (2)$$

where $*$ is a complex conjugate. The coherence estimate for the two channels i and j is calculated as in:

$$\gamma_{ij}^2(f) = \frac{|G_{ij}(f)|^2}{G_{ii}(f)G_{jj}(f)} \quad 0 \leq \gamma_{xy}^2 \leq 1. \qquad (3)$$

An example of four EEG channels carrying SSVEP response is presented in Fig. 2, while the Fourier power spectra of the pre-stimuli, stimuli, and post-stimuli periods are depicted in Fig. 3. The results of coherence analysis conducted for 1 s-long EEG periods with 500 ms overlap are presented in Fig. 4.

C. Overtone Mapping

We previously proposed a sound synthesis method called overtone mapping in which the fluctuation of multichannel EEG data are assigned to time-varying amplitudes of overtones from a harmonic series, generating "an auditory gestalt" from correlated time-series data [11]. We used this technique in this study and assigned the coherence between two EEG channels to amplitudes of a harmonic series. The basic algorithm of the

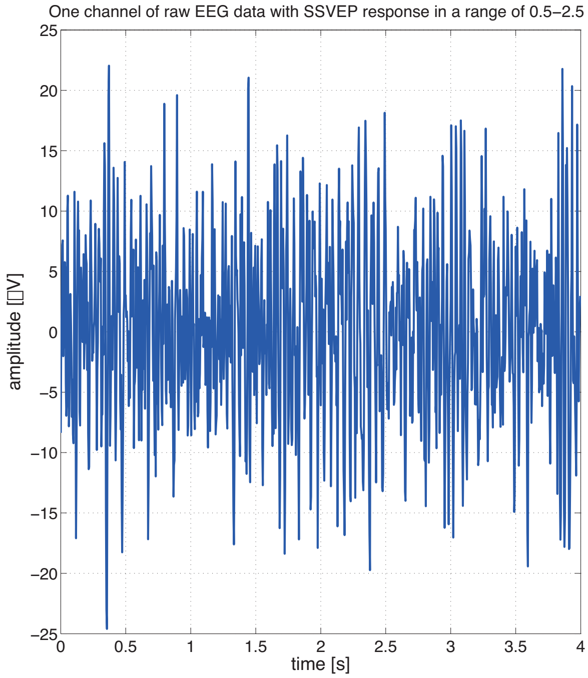

Fig. 2. The single EEG channel with SSVEP response. The visual stimuli was presented in a range of $0.5 - 2.5$ seconds.

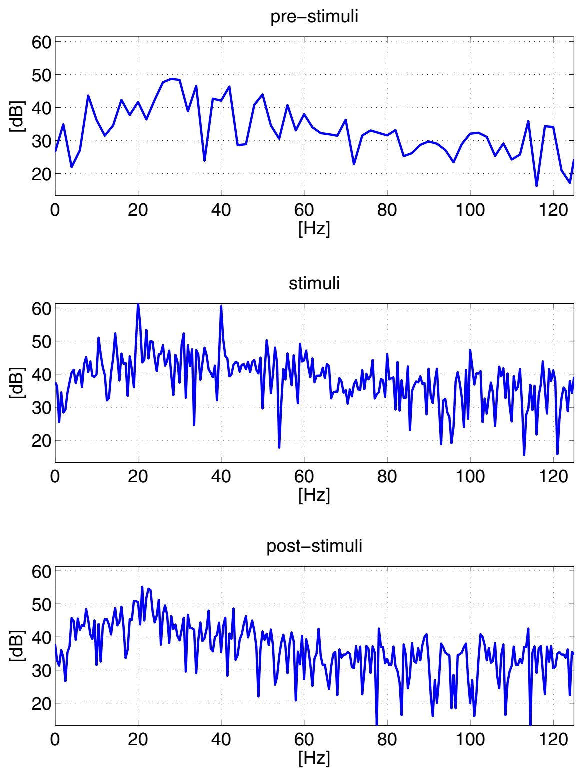

Fig. 3. The power Fourier spectra of the single EEG channel with SSVEP response as shown in Fig. 2 divided into three panels. The top and bottom panels represent EEG power spectral without SSVEP for pre- and post-stimuli periods respectively. The middle panel depicts the EEG power spectrum with SSVEP response with two distinct peaks at 20 and 40 Hz.

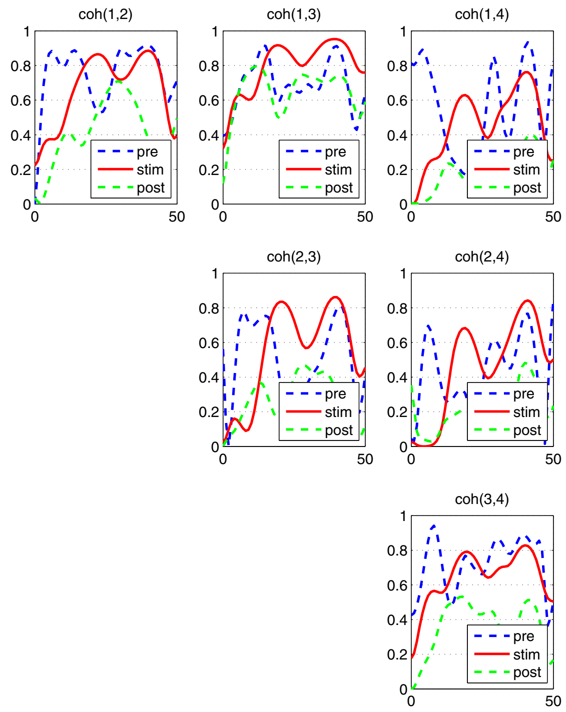

Fig. 4. The results of pairwise-coherence analysis as shown in Eq. (3) for all four pairs of the analyzed EEG signals as in Fig. 2. The results of the conference analysis is easier to classify already viable when compared with spectral representations as shown in Fig. 3. The two distinct "hills" at 20 and 40 Hz are related to the stimuli (solid red lines), while the dotted and dashed lines are from pre- and post-stimuli intervals without coherence in those frequency ranges, respectively.

synthesis is as follows. First, we determine the fundamental frequency then generate a harmonic series of sine wave that contains as many harmonics as frequency bins of coherence. Coherence is assigned to amplitudes of overtones, that is, the fluctuation of the nth bin of coherence is used as the amplitude of n^{th} overtone. When a frequency bin from the coherence array has a high value, the overtone assigned to that frequency bin sounds loud. When a frequency bin from the coherence array has a low value, the overtone assigned to that frequency bin sounds quiet. To summarize, the fluctuation of the coherence array delivers timbre change. We applied the above method to the sound synthesis in SuperCollider by analyzing the results in MATLAB with open sound control (OSC) protocol. In MATLAB, we calculated the coherence between specific combinations of EEG channels, which are physiologically well connected. We converted the coherence into amplitudes of overtones as the following equation:

$$A = 10^{\alpha(\gamma_{xy}^2(f)-1)/20}. \tag{4}$$

In the above equation, A represents amplitude of overtone and $\gamma_{xy}^2(f)$ represents coherence. Since the coherence value ranges from 0 to 1, the amplitude value A ranges from -α to 0.

III. SSR Data and Its Sonification

We used EEG data of four channels containing SSVEP obtained by LED flashing for sonification in this study. The length of the data is approximately 10 seconds and SSVEP occurs between approximately 0.5 and 6 seconds. We calculated 4 pairs of coherence from the data.

The fundamental frequency and Musical Instrument Digital Interface (MIDI) note number of the harmonic series corresponding to each coherence pair is shown in Table 1. The synthesized sounds are played in the loudspeaker setting as shown in Fig. 5. The subscript number for coherence (coh) represents a combination of EEG channels; e.g., speaker channel #1 plays back the synthesized sound from the coherence between EEG channels 1 and 2, and so on. We designed the fundamental frequencies to sound in harmony when multiple sounds occur at the same time in order to provide comfort and familiarity to the listeners.

TABLE I
The Fundamental Frequency and MIDI Note Number of the Column of Overtone Corresponded to Each Coherence

Coherence	Fundamental frequency [Hz]	MIDI note No.
coh_{12}	130	48
coh_{13}	164	52
coh_{24}	195	55
coh_{34}	233	58

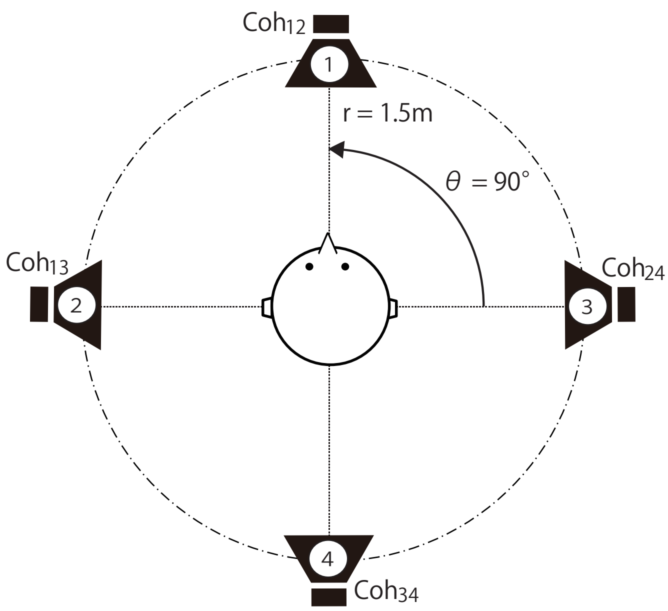

Fig. 5. The environment of hearing the sound.

IV. Evaluation Experiments Overview

We conducted two evaluation experiments for the proposed sonification method: The task for Experiment 1 was to detect the presence of SSVEP; the task for Experiment 2 is to identify the direction of SSVEP propagation. Our subjects were four men and two women in their early twenties. All the subjects were healthy and did not have any clinical histories in hearing andspeaking. They participated in the experiment upon the consent of the condition of the experiment. The experiment took place in the studio at the Life Science Center of Tsukuba Advanced Research Alliance.

V. Evaluation experiment 1 : SSVEP detection

The purpose of this experiment was to verify if the subjects could detect the presence of SSVEP by hearing the sonified sound. The experiment consisted of the listening tests and a questionnaire.

A. Procedure

1) Listening test: In the listening test, subjects were asked to detect and report the onset and offset time of the SSVEP response period using a Graphical User Interface (GUI) with a stopwatch function while listening to the sound. Before the experiment, subjects practiced understanding the sonified representation of SSVEP response using the sounds that did not appear in the experiment. The sonification sound for the experiment session was generated from the data described in Section III. The sound was repeated three times, and the total length was approximately 35 seconds.

2) Questionnaire survey: After the listening test, the subjects answered a questionnaire survey with the following questions about comfort and comprehension:

A. How comfortable was listening to the sonification sound?
B. How comprehensible was detecting the presence of SSVEP?

The evaluation was done with a 5-point scale, where point 1 corresponded to “bad” and 5 corresponded to “good”.

B. Results

The summary of the reported start and end times of the SSVEP response period is provided in Fig. 6. Short, dashed lines represent the mean value of the reported onset and offset times from all the subjects, and the solid lines individually represent the SSVEP response period reported by each subject. The wave plot provides the mean value of the four coherences. All the subjects detected the periods where the mean value of four coherences was the highest, and the variance of the onset-offset times between subjects was very small. All the subjects were able to detect a period in which a strong synchrony in the whole area of the brain occurred, and therefore were able to identify the SSVEP response by listening to the sonification.

The coherence values identified as the start and end of the SSVEP were asymmetrical: The majority of subjects reported the onset of SSVEP at $0.5 - 0.6$ mean coherence value, while the offset of SSVEP was reported at $0.3 - 0.2$ mean coherence value. The possible reasons for this asymmetry are the adaptation to the sound (usually the threshold of hearing takes a lower value, when the amplitude of a sound is gradually decreased, compared to when the amplitude is increased), and the steepness of the coherence change of the original data (i.e., more gradual in the rising phase in contrast with a sharp decline in the decreasing phase.)

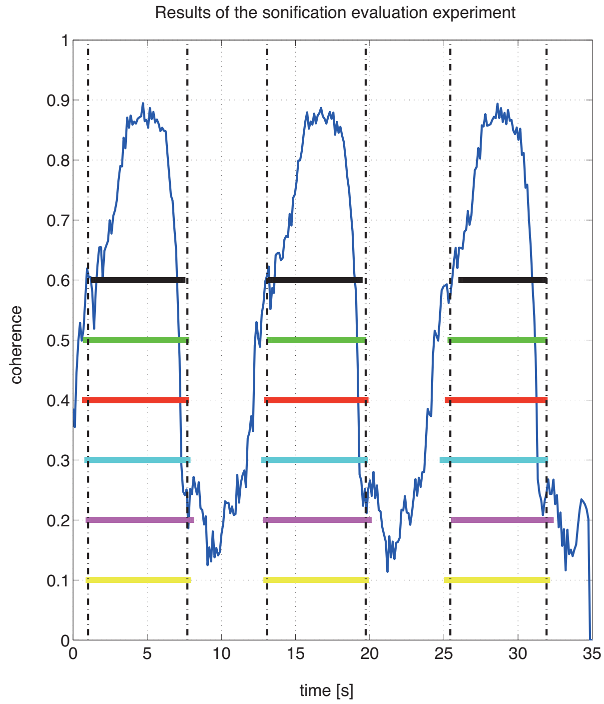

Fig. 6. The reported onset and offset times for Experiment 1. Solid lines: individual response; dash-dotted lines: mean onset and offset times across four subjects. The waveform plot shows the mean of the four coherence arrays.

TABLE II
QUESTIONNAIRE RESULTS FROM EXPERIMENT 1: THE MEAN SCORES FOR COMFORT AND COMPREHENSION ON A 5-POINT SCALE (1: BAD, 5: GOOD)

Questionnaire	A (Comfort)	B (Comprehension)
Mean score	4.3	4.5

The results of the questionnaire survey are shown in Table 2, with the mean scores for questions A (comfort) and B (comprehension). Both mean scores are over 4, which corresponds to the judgment of “slightly good”, showing that the presence of SSVEP is well represented by the proposed sonification method.

VI. Evaluation experiment 2: Propagation of SSVEP

The purpose of this experiment was to verify whether subjects could distinguish the process of the occurrence and propagation of SSVEP by hearing the sonified sound. The experiment consists of the listening tests and the questionnaire.

A. Procedure

1) Listening test: For the listening test, we presented the sonification in stereo and four-loudspeaker settings, and asked the subjects to describe the direction of the SSR propagation.

In the stereo-setting listening test, the sonification of two coherence arrays was presented. By using only three EEG channels out of four, we obtained two coherence arrays (e.g., coherences between channel #1 - #2 and #1 - #3, when leaving channel #4.) A session consisted of 32 trials with a three-second silence between trials, where each trial presented a stereo sonification based on two coherence arrays.

In the four-loudspeaker listening test, subjects listened to four-channel sonification based on four coherence arrays with all the EEG channels. The task of the subjects was similar to the stereo listening test, in which the subjects answered the direction of the SSVEP-response propagation. A session consisted of 24 trials with a 3-second silence between trials.

The direction of the SSVEP response between loudspeaker channels was varied for every trial by taking different EEG channel combinations.

In the experiment, subjects listened to the sonification, and answered the direction of the propagation by selecting the order of which loudspeaker sounded earlier compared to the others. Before the experiment, subjects practiced the direction judgment of the SSVEP-response propagation.

2) Questionnaire survey: After the listening test, the subjects answered a questionnaire with the following questions about comfort and comprehension:

A. How comfortable was listening to the sonification sound?
B. How comprehensible was the propagation of SSVEP?

The evaluation was done with a 5-point scale, where point 1 corresponds to "bad" and 5 corresponds to "good".

B. Results

Table 3 provides the chance level and the mean value of the accuracy in identifying the direction of the propagation in Experiment 2, for both the stereo and four-channel settings. In both settings, the mean value of the accuracy is better than the chance level. And the chance level of the stereo setting is half the value of the four-channel setting. By contrast, the difference in the accuracy of the subjects between both settings is only about 20%. We are considering the possibility that this difference in accuracy is due to the design of sound or the attention problem across multiple channels. These results confirmed that the subjects can distinguish the process of the occurrence and propagation of SSVEP by hearing the sonified sound.

Table 4 shows the mean score for the questionnaire for Experiment 2. The mean score on comfort is at the same level as Experiment 1, but the mean score on comprehension was much lower, at "slightly good" level. Even the subject who performed at 100% accuracy throughout Experiment 2 provided "slightly unintelligible" rating as well. Figure 7 shows this discrepancy between the actual accuracy (objective judgment) and the comprehensibility score (subjective judgment), showing that these two measures did not directly correspond. Many subjects who performed well on the identification reported the task being difficult.

TABLE III
THE CHANCE LEVEL AND MEAN ACCURACY SCORE FOR EXPERIMENT 2. THE SUBJECTS ANSWERED THE DIRECTION OF THE SSVEP PROPAGATION

Setup	stereo	4ch
Chance level	8%	4%
Mean accuracy	87%	69%

TABLE IV
QUESTIONNAIRE RESULTS FROM EXPERIMENT 2: THE MEAN SCORES FOR COMFORT AND COMPREHENSION ON A 5-POINT SCALE (1: BAD, 5: GOOD)

Questionnaire	A (comfort)	B (comprehension)
The evaluation points	4.5	2.7

VII. CONCLUSIONS AND FUTURE WORK

In the presented project we have focused on the synchrony-pattern analysis of the brain SSR by sonification. We proposed the sonification method as a representation tool that reflected the degree of the spectral correlation within pairs of EEG channels. We used the power-coherence analysis as a measure for the synchrony, which allowed us to capture the spectral similarity properties of the multichannel EEG data. The transitions in the synchrony patterns are represented as timbre (i.e., spectro-temporal) deviation and as spatial motion of the sound cluster.

To evaluate the proposed method, we conducted the experiments with human listeners. The listeners were asked to identify the SSR onsets and offsets from the multichannel sonified EEG. Our results showed that the proposed sonification approach based on the pairwise EEG coherence allowed for very accurate identification of the steady-state responses.

In future work we plan to improve the accuracy of our method in order to further elucidate the propagation patterns of steady-state responses. We also plan to construct a spatial three-dimensional "sound field" to simultaneously analyze a

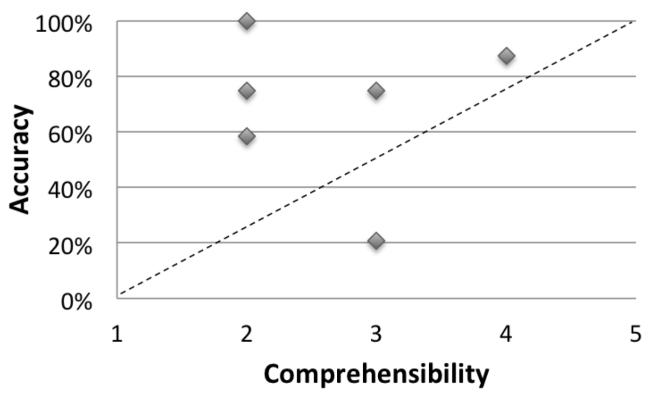

Fig. 7. The relationship between the comprehensibility score of the questionnaire and the accuracy of the identification in the case of the four-channel setting.

larger number of EEG channels carrying steady-state response, with an improved sound design that helps the listeners to better understand the propagation from both objective and subjective perspectives.

The presented research results are a step forward in developing multichannel brain synchrony analysis tools.

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