Listen to the Brain in Real Time
—The Chengdu Brainwave Music

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Abstract—Electroencephalogram (EEG) provides a window for the activity of the human brain. As a novel form of the brain-computer interface (BCI), the online/offline EEG data may be interpreted through its auditory representation which can be considered as a specific tool in EEG monitoring and analysis. In this work, after a comprehensive comparison of the various designs of brainwave music generations, a waveform event mapping system for music display in real time—the Chengdu Brainwave Music (CBM) is proposed, which is a special on-line BCI system. In CBM, the user datagram protocol (UDP) is adopted to transport EEG data from the recorder to a music generator. The CBM could possibly be used as an audio feedback tool in BCI, or a monitoring tool in clinic EEG, and a subject specified music therapy method.

Index Terms—Brain-computer interface, electroencephalogram, sonification.

1. Introduction

Understanding the most mysterious brain activities is a long-term goal of science. Many technologies, including high-density electroencephalogram (EEG), functional magnetic resonance imaging (fMRI), and magnetoencephalography (MEG), have been extensively utilized in recent years to address this goal. The EEG is a real-time series; if the low-frequency brainwave could be heard after translation by a special sonification rule, we may be able to directly “perceive” brain activity and its variation using our auditory system. As the frequency range of human hearing is large (ranging from 20 Hz to 20000 Hz) and a normal person can hear subtle differences in frequency, the hearing strategy of EEG may provide not only a real-time monitoring of brain activities but also a more sensitive way to detect the small variations in the amplitude and duration of brainwaves that might be ignored by conventional EEG technique.

To hear the hidden brain activities from an invasive scalp EEG has long been a dream of neuroscientists. The earliest attempt to hear brainwaves as music was made in 1934[1]. A “Music for Solo Performer” was later presented in 1965[2], and other similar music pieces followed. In most of these early works, however, only the amplitude of the alpha waves from EEG signals was utilized as the driving source of the musical sound. In the 1990s, various new music generating rules were created from digital filtering or coherent analysis of EEG[3]. Since the sonification of biological signals became popular, many artificial sounds, which were controlled by data or parameters extracted from data, were synthesized to represent the biological information, including the DNA sequences[4], neurobiological data[5], EEG[6], and so on. With high temporal resolution, the EEG auditory display can reveal some detailed characters of brain activities in real time.

A brain-computer interface (BCI) allows for direct brain-computer communication without using the muscular activity. To date, most efforts of BCI research have been aimed at developing technologies to help people communicate with computer systems or control mechanical tools, such as a wheelchair or a prosthetic organ. The BCI application in music is an interesting area for the development of new possibilities in recreational and therapeutic devices for people with physical and neurological disabilities[7]. Furthermore, in BCI framework, the feedback is important for the efforts of subject’s self-regulation, and the visual and simple auditory feedback can be used to improve the availability of control[8]. The artificial sound with certain pitch and timbre, or the sounds of specific musical instruments can be utilized as materials for neuron-feedback.

In this paper, first we critically compare the main strategies for listening to the activity of human brain, i.e. the basic methods to generate brainwave music. We then introduce the Chengdu brainwave music (CBM) system for real-time brainwave music including the data acquisition, data processing and music generation environment. The feature mapping rules are based on some intrinsic properties of waveform, such as amplitude, duration, and that of the musical tones, for example, the pitch, duration.
The user datagram protocol (UDP) is chosen for the communication between the computers with on-line data acquisition and music generation. We also discuss the significance of the brainwave music, and the applications of the EEG music representation in both medical and recreational fields, especially in BCI system. Finally, we summarize the specific use of the real-time brainwave music system for the investigation of EEG analysis and BCI feedback, and present an outlook to future work to assist the exploratory data analysis and understanding the functional mechanism of brain activity.

2. Brian Music Generation

In EEG monitoring, BCI, and EEG feedback, quick detection and identification of data patterns in real time are desirable. Auditory display offers the advantage to follow the events without the need to watch a screen. However, if we make the recorded EEG data audible directly by translating the brainwaves into audio waves, the results are noisy, even the prominent alpha wave frequency component can not be heard. Therefore, various strategies of the conversion from EEG to audible sounds have been proposed since 2002\(^9\), and ample artificial sounds synthesizers are utilized for display. In recent years, musical instrument data interface (MIDI) is widely used in music composition and performance, with which we can obtain quite pleased music pieces with specific instrument timbre just by inputting data to drive the interface. Music is generally regarded as an unique auditory art form\(^10\), and it is an approach of interaction in human cultures. It is believed that music can represent the message of human in a quite free way, especially for emotion and mental states. These facts indicate that to display the EEG with music or regulate the brain activity to control music may be cardinal in brain study.

There are three main categories of brainwave music systems according to the hierarchy of the features extracted for music generation. The first one is the parameter mapping, which is the oldest and simplest conversion as we mentioned in section 1, but there are still some recent works adopting such strategy with improvements\(^8\). The second is the event-based brain music that defines specific events as triggers for the beginning of music tones or other sound events\(^11\). This kind of mapping method focuses on some details of the temporal serial which indicates a musical rendering of the EEG, and it is convenient to be used in real time. Third, the brain is regarded as a network, and the brain working with some specific patterns are related to cognitive functions, therefore the model-based method may be designed\(^12\), and there are some applications in BCI based on this model\(^13\).

2.1 Parametric Brainwave Music

Because of the similarity of EEG waveform and music sound, the parametric mapping is the direct conversion of the EEG to its music representation. Hinterberger and Baier have proposed a device for the parametric sonification of EEG data\(^9\). The device allows auditory feedback of multiple EEG characteristics in real time. It is believed that human aural processing can deal with higher complexities of music than those currently used for scientific purposes.

In their works, EEG parameters were extracted and assigned to voices in a MIDI device, and a voice was assigned to a MIDI channel. The MIDI device of a common PC sound card provides 16 channels. Each channel needs three parameters to define: for an instrument, its pitch, duration and volume, and those were the essential characters of musical tones. Usually, the trigger frequency modulates the note pitch, and the amplitudes of the local maxima of brainwave modulate the volume. And in different frequency range, different orchestral instruments were chosen to play.

In a pilot study\(^8\), the participants were introduced to an attention task. They were instructed to focus their attention alternately on two different sounds: the music of EEG high frequency and low frequency. The results showed a significant difference between the two music parameters. However, it was difficult to decide to what extent and how the controllability or noncontrollability of a parameter is connected to the stimulus mapping properties. In a feedback task, the real cardinal stage is to detect specific motifs in the music patterns that can be related to a mental state or to a change between mental states.

2.2 Event-Based Brainwave Music

In order to explore the explicit meaning of EEG, to suppress irregular background and highlight normal and pathologic rhythmic activity, an event-based method has been proposed\(^11\). In this kind of method, specific data features were defined as triggers to playing of a sound from a pre-defined sound generator in the programming environments. For example, the local maximum was extracted to trig a note and the volume, duration and number of harmonics were all controlled by the features of events, thus the volume was set in a linear mapping of the voltage difference between the present maximum and the previous minimum in the time series, the duration was fixed with the inter-maxima interval, and the number of harmonics was controlled by the inter-maxima interval too. The space information in the multiply EEG data was represented by tones pitch in their work.

The significance of this work is that it can be implemented for on-line monitoring of clinical EEG and for EEG feedback applications. The event in the mapping rules is the bridge from EEG data to sound of music, thus the definition of that is the key question in the music generation. And the parameters of music are dependent on the features of the event.
2.3 Brian-Computer Music Interface (BCMI)

As in BCI systems, this brainwave music method is aimed at the exploration of the human thoughts. It is believed that the music is based on the EEG patterns which are related to some specific cognitive functions. The system can be called as brain-computer music interface (BCMI)\(^7\)[13][14], which uses the EEG directly to steer generative musical rules to compose and perform music on a MIDI-controlled mechanical acoustic piano.

In such a system, EEG frequency band and the signal complexity were used to control the music processing. The patterns of EEG would activate the different generative rules. The EEG patterns might not be exactly related to the subject’s real aim, the goal was to make the mapping rules control the music melody. For example, in order to obtain a pleased music, the computer music approach based on augmented transition networks (ATNs) was implemented\(^7\).

The EEG patterns here are the combination of the features in temporal or spatial dimension. Compared with the former methods, BCMI is regarded as a paradigm of BCI, and it is closer to the aim of representing the thoughts of humans. However, it depends on the technology of EEG analysis and the music generation rules.

3. CBM System for Real Time Brain Music

In our work, a system for real-time brain music, the Chengdu Brainwave Music (CBM) System, is designed in line with the on-line BCI system. The framework of the system is shown in Fig. 1. The EEG of the subject is amplified and acquired by computer PC1. The amplifier with USB interface communicates with PC1 which in turn controls the EEG recording and analysis. Another PC2 is utilized for music generation with MIDI, and it obtains the EEG data through UDP with wireless network. PC1 may also provide the visual feedback to the subject, while PC2 provides the music as an auditory feedback.

![Fig. 1. The framework of CBM for real time music display.](image)

3.1 Data Acquisition

The EEG is acquired with an EEG amplifier connected to a computer via a USB interface. The EEG signal is sampled at 1000 Hz and digitized with a 16 bit A/D converter in the amplifier. The resolution in amplitude is 0.5 μV, and the CMRR>110 dB. The filters of the amplifier are set to 0.01 Hz as the low frequency cut-off and 40 Hz as the high frequency cut-off. EEG usually is recorded from 16 Ag/AgCl-electrodes placed on the scalp, and referenced to the mastoids. The locations of electrodes are shown in Fig. 2.

The participants view the screen to control a ball move to the left or right. Each trial lasts for 6 s. During the time, the subjects try to imagine their arms, legs or tongue move. The tasks are the motor imagery, therefore the data used for analysis are usually from C3 and C4 (10-20-system), here are 5 and 6, respectively. The participants were paid reward after the experiment, and also informed consent was obtained.

3.2 Data Processing

The EEG data recorded by PC1 are transported to the music generation PC2 to compose music pieces. The data transportation is by UDP. The program for data sending is embedded in PC1 for EEG recording, while a data receiving client is on the music generation PC2. These programs are all written with C language.

In this work, we utilize a method based on waveform event for mapping. The details are shown in Fig. 3. The EEG data are analyzed to extract the amplitude, period, and power, and these are reflected by the MIDI notes’ characters, the pitch, duration, and intensity (volume). The event that triggers the MIDI engine to perform is when the brainwave crosses the baseline. The timbre of the notes is fixed with piano. The conversions are according to the scale-free power law followed by both EEG and music\(^15\).

![Fig. 2. The locations of electrodes.](image)

![Fig. 3. The mapping rules.](image)
3.3 Software

The software in our work includes two parts. One part is the EEG acquisition and recording, which is based on the EEG amplifier bottom driver and SDK (standard development kit). The software interface is developed by Borland C++ Builder. The other important part is the music generation environment.

In the present work, Max/MSP, a software programming environment optimized for flexible real-time control of music system\(^8\), is chosen for on-line brain music performance. It is currently the most popular environment for programming of real-time interactive music performance system. Max/MSP is a very mature, widely accepted and supported environment. It allows a graphic interface to develop the program, and the visual subjects in the environment are the units for programming. Therefore, it also supports arithmetic or extended functions and allows new subjects to write with C language. In this work, the UDP receiving subject and the music mapping subject are both programmed with C language based on the SDK of Max/MSP.

3.4 Examples

As a pilot study, we use the EEG data from a motor imagery task. Fig. 4 and Fig. 5 show the results. Fig. 4 corresponds to the imagination of the left arm’s movement, while Fig. 5 is for the right arm. We can observe that the EEG data from C3 and C4 are quite similar in waveform, but they have some differences in frequency bands, and so, in the MIDI notes, the varieties are obvious.

Fig. 4. The EEG data in C3 (the first line) and C4 (the third line), and MIDI notes (the second and fourth line) when the subject imagine the movement of the left arm.

Fig. 5. The EEG data in C3 (the first line) and C4 (the third line), and MIDI notes (the second and fourth line) when the subject imagine the movement of the right arm.

4. Discussions

The musical representation of human EEG is a novel attempt in brain investigation, and we believe that it can be a window for the brain functions. Compared to other music, the brainwave music contains biological information. From this view, the music of EEG can be regarded as an auditory display of the brain activities, which make us understand it through listening to the brain.

Whatever the methods used for music generation, the brainwave music sounds are the auditory reflection for the EEG features related to human mental states. The amplitude, which is the most important character in temporal domain, depends on the mental activities. For instance, the sleep EEG usually has voltages approach to 150 μV, while it is less that 50 μV during quiet awake state\(^16\). Another essential character of EEG is frequency. EEG frequency range usually are divided into six bands: slow cortex potential (SCP), delta, theta, alpha, beta and gamma band, respectively. The neurophysiologic origins of oscillatory activities within these bands are not known in detail, but it is believed that the mechanisms of brain activity are related to these bands and these rhythms are from specific positions of the brain. Some animal experiments\(^17\) revealed the following facts: the spindle oscillations in the alpha band are generated in the thalamus; the SCPs are elaborated in the neocortex; the delta band comprises of different rhythms with different mechanisms in the thalamus and neocortex; and gamma band is activated in pattern recognition tasks and focused attention.
of the visual system. Such kind of information is considered in the brain music mapping rules\cite{10}. In addition, the nonlinear features are also used in EEG investigation, and some results show that the different states of EEG have different scaling properties\cite{11}. In CBM, we have considered the power law followed by both EEG and music\cite{12}.

Some EEG characters mentioned above are apparent in a visual waveform, but the others are not easy to observe on the screen, such as the frequency and scaling properties. Therefore, listening to the brain is a useful approach for EEG understanding and analysis.

There are a number of advantages to perceive the brain via an auditory music. First, the human auditory system has higher resolution than visual system in temporal aspect. Second, researchers hypothesized that the inherent ability of the auditory system to process multiple auditory streams in parallel, in contrast to the human visual system’s serial processing of multiple objects\cite{13}. Finally, the human aural processing can deal with much higher complexities than those used for scientific purposes, because human have the ability to distinguish between several simultaneous voices or instruments even in a noisy environment, which provides a good reason to use music to deal with multiparametric data set, such as EEG\cite{14}. At last, listening to music is particularly comfortable and interesting compared to staring at the screen.

The possible applications for real-time brainwave music system are wide in medical, scientific and artistic fields. It can be used as an EEG monitor or alarm in daily monitoring and for specific neuropathy such as epilepsy\cite{15,16}. And the brainwave music has potential effect on music therapy. There is an attempt to use brainwave music to treat the insomnia\cite{17}, and the proposed brainwave music generation is used in rat experiment. The results show that the music from sleep EEG of rats can improve their arouse states. In sense of science and technology, the brainwave music system is an extended version of BCI, thus the interface for music can be utilized for music performance or feedback in control. It may be a tool for monitoring the brain and the music cognitive research. Furthermore, the system is valuable in amusement, as everyone can compose music for oneself just by the system.

However, there are still problems in such a system. The most essential problem is how to keep balance between science and art. A direct rendering may cause a stochastic MIDI sequence, which has less music aesthetic feeling, and if more composition rules are considered, the more biological information may be lost, such as the BCMI system\cite{18} and our previous work of brainwave music generation based on wavelet analysis\cite{19}. Moreover, the mapping from EEG to music also depends on our understanding of the brain. Thus the intrinsic scientific meaning of a mapping rule strongly depends on the development of the brain science. By the way, the effectiveness of CBM in feedback or therapy needs to be evaluated with experiments, thus a lot of works need to be done in the future.

With the development of signal processing, brain function and computer music composition, the real-time brainwave music will be more scientific and artistic. We expect that we can use the EEG for direct brain communication or online composing with further training and to understand human brain deeply.

5. Conclusions

A system for brainwave music generation in real time is quite new and interesting in BCI or EEG analysis. The conversation from EEG to music is based on scientific and artistic knowledge and hypothesis, and can be utilized as a valuable tool in EEG monitoring for display and analysis. Based on the music power in human physiological state and emotion, the brainwave music could reveal the brain activity in a multimodal presentation. The CBM is a primary effort in translating brainwave to music by the common intrinsic properties of both EEG and music, the obtained music sounds good, and the applications in BCI based therapy, clinic monitoring or just for amusement are just at the beginning.

References


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