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Léo Chédin[1], Giorgia Cantisani[1], Benoît Montigné[2], and Daniel Pressnitzer[1]

[1] Laboratoire des systèmes perceptifs, Département d'études cognitives, École normale supérieure, PSL University, CNRS, 75005 Paris, France
[2] École Nationale Supérieure des Arts Déco (ENSAD), 75005 Paris, France
[leo.chedin giorgia.cantisani daniel.pressnitzer]@ens.psl.eu

Abstract. Using electroencephalographic signals (EEG) for music creation has a long and distinguished history. Here, we introduce MaxMuse, an open-source streamlined system combining a low-cost, consumer-grade EEG headset (Muse2, InteraXon) and a widely used real-time graphical programming language (Max/MSP, Cycling'74). Pilot benchmarks show that the system is appropriate to process so-called "alpha waves", often used in brain-computer interfaces, but also auditory-evoked responses. Overall, we suggest that MaxMuse may facilitate novel interactive musical applications for which EEG signals can easily be collected from the composer, performer, or even from the audience.

Keywords: Brain-computer interface, interactive performance, auditory EEG.

1 Introduction: Music and Brain-Computer Interfaces

It has been argued [1] that the first ever brain-computer interface (BCI) may be traced to Alvin Lucier's *Music for Solo Performer* (1965), even before the term BCI was coined. In this piece, the performer was fitted on stage with a few electroencephalography (EEG) electrodes intended to collect brain-related electrical activity from his scalp, and the amplified analog signals were used to drive a set of motorized percussion instruments. Many other musical pieces have since involved EEG. A non-exhaustive historical list features Richard Teitelbaum's *Spacecraft* (1967), where EEG was used to control a Moog synthesizer; Roger Lafosse & Pierre Henry's *Corticalart* (1971), which attempted to distinguish between different types of EEG signals; David Rosenboom's *Ecology of the skin* (1970), where EEG responses were collected from members of the audience. More recent endeavors have introduced semi-standardized setups such as *Biomuse* (see [2] for a review).

Even if it has obvious theatrical appeal, the cumbersome nature of the current EEG systems restricts their domain of application. Research-grade systems require scratching the head of the user to apply conductive gel for each electrode, resulting in a long and failure-prone setup procedure. This is not ideal if, for instance, a composer at home wants to iterate on a musical idea quickly. Also, such a setup is not practical for interactive performances involving *e.g.* the large-scale collection of EEG signals from an audience.

The first goal of this demo paper is to introduce an easy-to-use EEG system for interactive musical performances. In the current implementation, the system uses a low-cost headband with little to no setup time: the Muse2 headset (InteraXon). The headbanded is then interfaced with a real-time programming language widely used by musicians: Max/MSP (Cycling'74). The interface is realized by external Max objects that we developed, which are open source and freely available[1].

A second goal of the paper is to provide pilot benchmarks for the type of EEG signals that can be expected from the system. The Muse2 headset is marketed as a meditation aid, so it is optimized for "alpha waves", the most prominent oscillatory activity in EEG signals [3]. Most early musical performances focused on alpha waves and we show example recordings of such signals. However, in musical settings, EEG responses evoked by sound may also be of interest. We further demonstrate that our system can represent sound-evoked responses, by showing "auditory steady-state responses" [4] to amplitude-modulated noise. Finally we discuss how the system may be used and extended for future artistic applications.

2 Technical implementation

2.1 The Muse2 headband

The Muse2 headband is a commercial device marketed as a meditation aid. It collects signals from brain activity (EEG), blood flow (photoplethysmography), and motion (accelerometer and gyroscope). Although paired with a proprietary app by default, the device is interesting for research and creation as it enables direct access to its raw signals. In terms of EEG, the device features 5 electrodes (Fpz, AF7, AF8, TP9, and TP10 in the standard EEG nomenclature) sampled at 256 Hz, giving access to 4 real-time signals (Fpz is used as ground by default). Moreover, the headband's charging port can be used to connect an additional electrode.

2.2 The MaxMuse library

Our main contribution is an open-source library of external objects for the Max MSP software environment for a seamless interface with the Muse2 headband. The core of the library is developed in C/C++ using the official Min API to Max.

The architecture of the system is as follows. First, the Muse2 signals are broadcast using the *Lab Streaming Layer* (LSL) protocol, an open research standard for EEG setups. LSL streams are created by means of free third-party software such as *BlueMuse* or *Petal*. Then, MaxMuse objects take care of LSL streams search and selection.

The most important objects of the library are *receiver* and *receiver~*, which are almost identical. They connect to an LSL stream using conditions (device name and/or

[1] https://github.com/lched/MaxMuse

stream type) and expose the incoming data in the Max environment. The *receiver* object receives messages at about 256Hz, which can be used to control signal processing objects. The *receiver~* object performs near real-time resampling to the sampling rate used by Max/MSP, allowing to treat the EEG signal as any other musical signal and opening the full range of Max functionalities. This could be useful for *e.g.* direct sonification.

These two objects have as many outputs as there are channels in the selected LSL streams, allowing, on the one hand, to select a subsect of electrodes, or, on the other hand, to combine several headbands. The library also includes helper objects to compute meaningful EEG features, such as power in specific frequency bands.

3 Pilot benchmarks

3.1 Alpha waves

As described in the introduction, many past musical applications were based on alpha waves [3], which are prominent EEG oscillations in the 8-12 Hz frequency band. Such waves are known to be modulated by arousal, and in particular, their amplitude is expected to increase when the eyes are closed. Our first pilot benchmark attempted to replicate this observation.

We used the MaxMuse environment to record EEG signals from a single participant who alternated periods with eyes open or eyes closed, over 15 successive cycles of 10 seconds. Figure 1, left, shows the resulting average spectra. We used an empirical pre-processing pipeline that has not been optimized yet: average of TP9 and TP10 electrodes, notch filter at the power line frequency of 50Hz, bandpass filter between 3 Hz and 40 Hz.

As expected, the power spectral density shows a clear peak in the alpha region when eyes are closed compared to when eyes are open. There is also a peak for low frequencies in the eyes open condition, which we attribute to the participant's blinking. Such artefacts are well known for EEG and there are classic means to mitigate them, such as thresholding. There are also two artefacts at about 23 Hz and 46 Hz, which are specific to the Muse2 headband and of unknown origin.

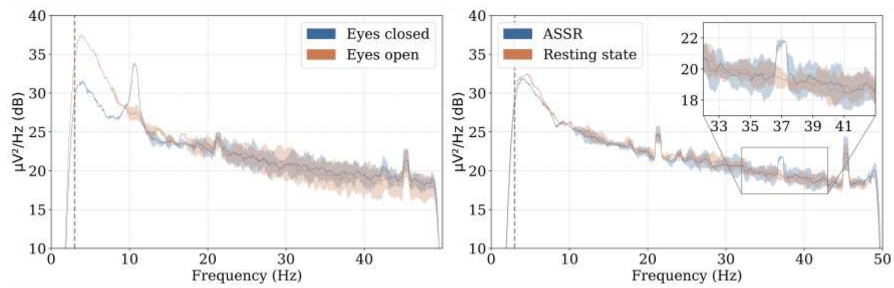

Fig. 1. Left: Average power spectral density with eyes closed (blue) or eyes open (orange) over 10-s periods. Colored patches represent the standard deviation about the mean. **Right:** Same, for the auditory steady state response to a 37-Hz amplitude modulated noise or silence.

3.2 Sound-evoked responses

In musical settings, it may be desirable to extract EEG responses related to sound. There are many types of such responses [4], but we initially tested whether the MaxMuse system was sensitive to the "auditory steady state response" (ASSR), whereby the EEG reflects the amplitude-modulation spectrum of the acoustic stimulus. We used broad-band noise with 100% sinusoidal amplitude modulation at 37 Hz as a stimulus, the modulation frequency being in the range of the largest expected ASSR. Five 60-s long periods of sound alternated with equivalent resting periods.

Figure 1, right, shows the resulting spectra, using the same non-optimized pre-processing pipeline as for the alpha waves experiment. A clear peak at 37Hz is observed in response to the amplitude modulated sound. This result is interesting as the Muse2 electrode placement was not optimized for collecting auditory responses.

4 Discussion and Perspectives

We implemented a real-time system enabling the easy deployment of BCIs in musical settings. Other systems with a similar aim exist, such as *MusePort* or *Mind Monitor*, but to the best of our knowledge, our library is the only free and open-source solution based on open protocols. As a result, our solution is extensible. For instance, we are experimenting with a freely positionable dry comb EEG electrode to improve the quality of auditory responses. Moreover, the library should work with any EEG device supporting the LSL protocol, with little to no change to the source code.

The MaxMuse system makes it simple to experiment in real-time with alpha waves in musical performances, as pioneered by Alvin Lucier and extended by many others. Furthermore, the possibility to extract auditory-evoked activity opens new possibilities: decoding of various aspects of musical perception at the individual level [5] or even synchronization across individuals as a result to music listening [6]. We hope that MaxMuse will help artists freely experiment with the new possibilities offered by such recent scientific advances.

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