A BCI-Based Application in Music: Conscious Playing of Single Notes by Brainwaves

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The relationship between the brain and music represents a fundamental field for investigation in HCI (human-computer interaction), for example, in games, virtual reality, and digital entertainment, due to the impact of music on human experience, emotions, and cognitive processes. For a low cost and the possibility of real-time analysis, the brain computer Interface (BCI) offers the potential for using music in HCI-related applications, as in games and entertainment.

In many studies related to music and the brain, BCI devices have been used both for psychological aims and for neuro-feedback-based therapy. In our work we focus on the possibility of enabling users to consciously play a specific musical note through low-cost BCI devices by reading subjects' brainwaves under a combined paradigm of audio, gesture, and visual stimuli. The results encourage further developments and future research.

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1. INTRODUCTION: AIMS AND MOTIVATIONS

The increasing interest in commercial noninvasive brain computer interface (BCI) devices and their application in different research fields [Friedman et al. 2007; Nijholt et al. 2008; Pfurtscheller and Neuper 2011; Calore et al. 2012] is mainly due to the low cost and portability of this equipment. The latter characteristic makes BCI devices particularly suited for many kinds of experiments involving virtual [Friedman et al. 2007; Mulder 1994] and real [Nakamura et al. 1999] situations and a larger number of subjects.

BCIs [Allison et al. 2007] are simplified medical EEG tools. Initially designed for games, and later extended to control electronic devices or software environments, BCIs enable the interpretation of the electrical material collected by sensors positioned on the user's scalp.

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In studies related to music, or the relationship between music and the brain, BCI applications concern both the psychological sphere [Skaric et al. 2007; Wickelgren 2003] and neuro-feedback-based therapy [Minsly 1981; Pascual-Leone 2001], and the conversion of EEG signals into musical notes [Dan et al. 2009].

Among the works considered, not one seemed aimed at detecting a specific characteristic of the human brain that allows making subjects able to reproduce the same single sound, thus reducing musical or brain training time. In our work we investigate the possibility of enabling users to consciously play a specific sound that is a specific single musical note via BCI devices in order to read the users' brainwaves, for application in games, entertainment, multimedia [Ebrahimi et al. 2003], and human-computer interaction. The novelty of our work consists mainly in allowing users, whether they are musicians or not, to consciously produce a specific prelistened single note via their own brainwaves only, or with the help of reinforcement stimuli; in the latter case in order to reduce training time (i.e., the number of listening occurrences of the note needed by users to reproduce it exactly). The application to entertainment is evident: music applications, games, virtual environments, and DJs could benefit from this approach.

In the first section of this article, we describe the materials and methods used in the experiments. Section 2 concerns the experiments performed and the corresponding results. Finally, in Section 3 we discuss the results and future developments.

This work opens new scenarios for further development, for example to obtain complex melodies, but also for future research in exploring relationships between music and different brain cortical rhythm schemata.

2. EXPERIMENTAL SETUP: MATERIALS AND METHODS

We designed two experiments, targeted at investigating the different responses of individuals to music and their ability to reproduce music with "as short as possible" training.

The experiments were performed in two steps: in Experiment 1 we registered unconscious EEG signals of brainwaves produced by different subjects. The registration was realized using a BCI device. The detected signal was processed by the application specifically developed for the experiment, with the aim of transforming the registered brainwaves into diferent sounds. The specific objective of this experiment is to verify if it is possible to identify a different cerebral characteristic for each individual, or whether we could find a common EEG pattern in individuals. In order to achieve this aim, our work tries to detect characteristics or value ranges which will lead us to Experiment 2. This consists in verifying whether subjects could be trained to consciously reproduce a single note via a BCI device and specific software by listening to audio or through other reinforcement stimuli only. We chose to use commercial BCI devices, after having verified their reliability, taking advantage of their portability and low cost, which makes them particularly suitable for entertainment applications.

Two BCI commercial devices are (mainly) currently used by the scientific community due to their power and because the are easy-to-wear: the Emotiv Epoc[1] and the Neurosky Mindwave.[2] These BCIs not only enable users to control IT environments but also allow us to collect and analyze different kinds of cerebral cortical rhythms; both devices are widely used in the ICT community. We chose to apply the BCI technology to the music field, where many studies have been conducted on the brain, EEG, and the mutual influence of mental states on music and vice versa [Schürmann et al. 1997; Marini et al. 2012]. For the purpose of the experiments, we decided to use the Neurosky Mindwave; of course, its use also represents a challenge, due to its apparently lower

[1]http://www.emotiv.com/researchers/.
[2]http://www.neurosky.com/AboutUs/BrainwaveTechnology.aspx.

potential compared to Emotiv Epoc. In fact, while the Emotiv BCI device reads brainwave data from fourteen sensors, the Mindwave provides just one sensor, positioned on the frontal area of the user's scalp. However, the Mindwave BCI is more comfortable for users, both for the ease in positioning the device on the scalp and because it uses a dry sensor, while the Emotiv uses wet sensors. Moreover, many studies [Nardi et al. 2005; Zumsteg et al. 2004] confirm that the music functions that are of interest to our work are related to the premotor frontal cortex area where the Mindwave sensor is positioned. Another advantage consists in the wireless communication between the Mindwave and the computer during the collection of data, which is particularly interesting from an entertainment perspective.

BCIs collect several cerebral rhythms grouped by frequency. Activity in the alpha band (7 Hz–14 Hz) is usually related to relaxed awareness, meditation, and contemplation. Beta band (14 Hz–30 Hz) is associated with active thinking, active attention, focus on the outside world or on solving concrete problems. Finally, activity in the gamma band (30 Hz–80 Hz) is considered related to cognitive processes involving different populations of neurons and to the processing of multi-sensory signals. We decided to use all the registered brainwaves, excluding Theta, due to their low activity in the waking state. Brainwaves registered through the Mindwave BCI device were sent to Processing,[3] an open-source programming environment containing a Java library, allowing the development of a Java application realizing the connection between Processing, the MindWave BCI and Max 6,[4] a popular environment for visual programming, specifically developed by Cycing '74 for applications in music and multimedia.

2.1. Experiment 1: Reproducing Music by EEG Brainwaves Interpretation

We can deduce (also referring to other work [Mauri et al 2010; Banzi and Folgieri 2012]) that people differ in their response to the same stimuli in the same situations. What we have tried to do in this experiment is to create an application that reads the subjects' EEG signals and transforms them into sounds, to see whether there are more similarities and/or differences in the "music of the brain". In other words, we were looking for a mix of characteristics individuating each subject, so that we could consider each subject as a specific musical trace, and state the similarity between the music and the brainwaves [Hodges 2002] specific to each individual; or whether we could identify characteristics or common patterns which would help us to create, in the second experiment, an environment allowing users to play, consciously, a specific musical note.

To obtain a music trace corresponding to brainwaves, we used the EEG signal as the input for the application created with Max.

We chose seven subjects, three women and four men between 14 and 49 years of age. The Difference in age was considered potentially relevant for the variability of the results. Each subject performed the test separately in a comfortable environment, to reduce variation induced by external interference. Each EEG registration session lasted two minutes, during which subjects were resting, they were asked not to close their eyes, speak or move. We then recorded the subjects' brainwaves, sending the input to Max in real time, to be processed and translated into sound overlapped to a loop.

We wrote a few lines of code to read the data in order to draw the graph of the EEG signal and to send the signal, collected by the BCI, from Processing to Max. We had to set up a patch for Max to read and play the music. In the Max application, we introduced a keyboard to send the right value to the midi synthesizer to create the note in MIDI notation. The last part of the application was designed to manage alpha, beta,

[3]http://www.processsing.org.

[4]http://cycling74.com/products/max/.

gamma, and delta brainwaves, passing them through a filter, a variable gain amplifier, and a modulator. With this configuration, a MIDI note was generated by alpha waves, while an eye blink, if present, provided the delay for the note. The MIDI note was then converted into its corresponding frequency and used to generate a saw-tooth signal. In addition, the signal from the beta waves was used to modify the phase of the signal, which was afterward sent to a filter in a notch configuration (eliminating the central band of the signal and allowing listening to the lower and higher band frequencies). After filtering, the signal was sent to the input of a variable gain amplifier to control the capture and release of the signal. Regulation of the general reproduction volume was obtained by limiting the amplitude of the signal to avoid distortions on the output audio signal. The delta and gamma waves were then used to modulate the output signal in amplitude. Finally, a digital-analog converter transformed the digital signal produced by Max into an analog signal reproducible by the amplifiers.

2.1.1. Experiment 1: Results. The collected raw data was graphically analyzed, in order to understand if there were common characteristics or specific patterns representing an individual's cerebral response.

Figure 1 shows the results collected for all the subjects, grouped by cerebral rhythm so as to obtain a visual comparison for a first evaluation of the different or possibly common patterns among subjects, independently of age, musical background or preferences. Alpha, beta, and gamma rhythms are reported.

The audio track produced by the EEG rhythms could be listened to on the website that collected the experiments' sources and results.[5]

Comparing the graphic representations of the various cerebral waves registered for each subject shows, as expected, that each individual has a unique cerebral track. The sounds produced via interpretation of the EEG registered waves exhibit this characteristic.

From the experiment, it was not possible to detect markers that allowed us to recognize the different subjects. The differences were not only evident among subjects, but we also detected differences in the same subject during different test sessions. Moreover, we also observed that there were similarities among the subjects' brainwave activities (in raw data) that were significant enough to perform the second experiment, consisting in the search for EEG wave value ranges corresponding to specific sounds (i.e., single musical notes) listened to by the subjects.

2.2. Experiment 2: Conscious Reproduction of a Single Musical Note

This experiment was performed to realize two objectives:

(1) to test the application, to include the results from the first experiment, and to refine the efficacy of the software tools; and
(2) to train the subjects to perform the task of mentally evoking a single musical note from the received stimuli and to transmit the brain signal via the BCI device to the application so as to reproduce the sound heard.

The second objective also concerns the investigation of the functioning mechanisms of the human brain and, especially, of the subjects' ability through training to produce a specific musical note by imagining the sound.

The second experiment concerns a problem-solving task, hence among all the brainwaves read by Mindwave, we chose the beta rhythm to reproduce the musical note because, in fact, it is considered in the scientific literature as the one most involved during problem-solving [Bhattacharya et al. 2001; Zumsteg et al. 2004].

[5] http://www.bside.unimi.it/brainmusic/bm.html.

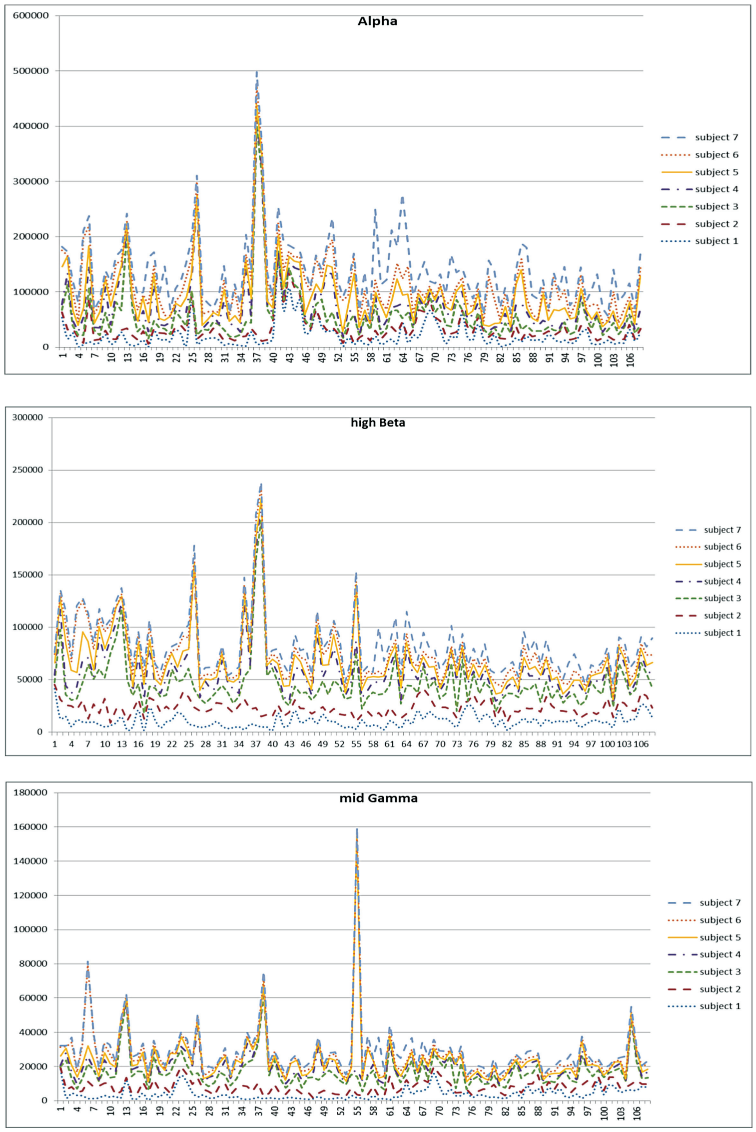

Fig. 1. EEG signals and brainwave rhythms from the seven subjects of the experiment.

Experiment 2 involved four subjects, three males and one female. The subjects were immersed in a familiar environment, wearing headsets, and completely isolated from the external world, remaining focused on listening to the sound in the headset (the single note). In the first phase of the experiment we created a patch in Max, consisting of a simple metronome which sent to the MIDI keyboard the value 69, corresponding to the note A, for 1000 milliseconds. After this we followed the same procedure for the value 37, corresponding to the note C, and for the other musical notes.

Using the same method as Processing in the previous experiment, we recorded beta rhythm data, reading the oscillations induced by the note A (LA) and C (DO), and so on, for the beta rhythm. To do this, we made two recordings: the first without any acoustic stimuli and in absolute silence; the second with only the sound of the notes A (LA) or C

Fig. 2. The image shown by the Processing sketch.

Table I. Examples of Notes and Associated Visual and Motor Stimuli

Note	Visual stimulus	Motor stimulus
A	orange	Knock the first finger of the right hand on the thumb of the left hand
C	blue	Knock all the fingers of the left hand on the palm of the right hand

(DO), and so on, played for one second, thus allowing us to observe differences between the signals in the two recordings.

For all the musical notes, we compared the curves related, respectively, to "listening to the silence" (the baseline) with listening to a specific musical note. The two curves differed but not as much as expected: in fact, the beta waves seem to be comparable in both cases. After some observation, it became clear that in the presence of a note, beta waves often gave a specific range of raw data values. For example, for note A, raw data values were often in the range (32000;35000) in μV, while for note C (DO), the raw data range varied in the range (23000;27000). Moreover, the training time to get the subject to reproduce the notes was too long: 3-4 tries were needed before success. We assume that the difficulty was not on the computer side (signal interpretation), but rather on the subject's side, given the difficulty in focusing only on the sound and avoiding distractions.

Reducing training time is fundamental to obtaining an easy-to-use tool [Blankertz et al. 2006]. We therefore decided to apply reinforcing stimuli, as suggested in the scientific literature [Peretz and Zatorre 2005; Zatorre et al. 2007]. The chosen stimuli were visual and motor stimuli associated with the audio stimulus of the selected note. The visual and motor stimuli reinforced the state of concentration in the subjects. The reinforcement stimuli were implemented by asking the subjects to make a gesture when an image and the note were presented during one second. For each note, a specific gesture and a specific image were selected (see Figure 2 and Table I; the letters "LA" represent the Italian name for note A). In this way we adopted a combination paradigm made up of the visual (the various images shown by the application) and the audio (the note played by the software) as mnemonic mechanisms, involving the participating individuals (the gesture was chosen by the subjects), After the training via a combination of stimuli, the subjects were invited to mentally evoke the the colors they saw and the note they listened to previously, associating the corresponding motor stimuli. Adopting this paradigm, the training time was reduced, in all cases, by about 40 to 50%.

As already stated, to perform this experiment we used Max and Processing together. Processing wrote the EEG data collected by the BCI device to a file. Then the data was processed and transferred to a worksheet. The aim of this phase was to understand which value range corresponds to hearing the notes in the presence of visual and motor stimuli. When the beta waves reach a value in the defined range, Processing sends the number corresponding to the MIDI value to Max [Dan et al. 2009]. When the value is received, it is sent to the controller MIDI, playing the corresponding note.

2.2.1. Experiment 2: Results. In the following, we show a graphic comparison of the beta waves collected during stimuli-reinforced listening to the musical note and during the reproduction of the same note (e.g., note A). The peak in beta waves corresponds to the sound of the note.

The presence of the reinforcing stimuli does not change the range of values identifying each note. For example, for note A the raw data values are always in the range (32000;35000), while for note C (DO), the range is (23000;27000), similar to the ranges without the reinforcing stimuli. We obtained similar results for all the subjects.

After a few minutes of training, the subjects were able to reproduce the notes by just thinking of them, with an immediate success in about 40 to 50% of the cases.

From Experiment 2 we obtained the expected results. In fact, after a short audio training and in combination with a visual stimulus and a motor task, all the subjects were able to reproduce the notes requested. This technique is often used in a similar way to train users in executing virtual actions on a computer, such as rotating a cube or linking a BCI to an electronic device to control the device itself [Ebrahimi et al. 2003; Friedman et al. 2007].

Apart from obtaining the first prototype for creating sound by brainwaves (one of the goals of this work), the experiment demonstrates that there is a correlation between the execution of an action and the will to execute it; also when the action is mainly nonmotor. Moreover, using the combination paradigm described previously reduces the rime for the training phase.

3. CONCLUSIONS AND FUTURE DEVELOPMENTS

The results of the experiments allowed us to further refine our tools, thus reducing the training time and allowing a generic user to reproduce any single note.

These results also made it possible for us to verify that by using an audio stimulus only, a subject would need a long training period to reproduce a proposed target sound. In fact, only after listening to a note four or five times, in three to four attempts, were subjects able to correctly reproduce the note.

Better results were obtained by adopting a combination paradigm, thus we adopted a paradigm made up of the visual (the various images shown by the application) and the audio (the note played by the software) as mnemonic mechanisms, involving the participating individuals (the gesture was chosen by the subjects), In this way we increased the subjects' ability to focus on the task, with a resulting increase and differentiation in beta waves. Consequently, a subject is able to efficiently reproduce the specific target note. The software we developed includes these results, so the necessary training time was greatly reduced.

We have integrated in the tool we developed the collected information, so the application implements the following characteristics:

—each note (to be reproduced later) is listened to just once by the users;
—before reproducing the target note, the program instructs the user by asking him/her to associate a simple gesture (the software suggests a different gesture for each note) while listening;
—while listening to each note the software shows the associated image (the name of the note on a different note-specific color background).

Thanks to this paradigm, a generic user can be trained to listen to all the seven notes in the same session, and to later correctly reproduce them just by evoking the associated

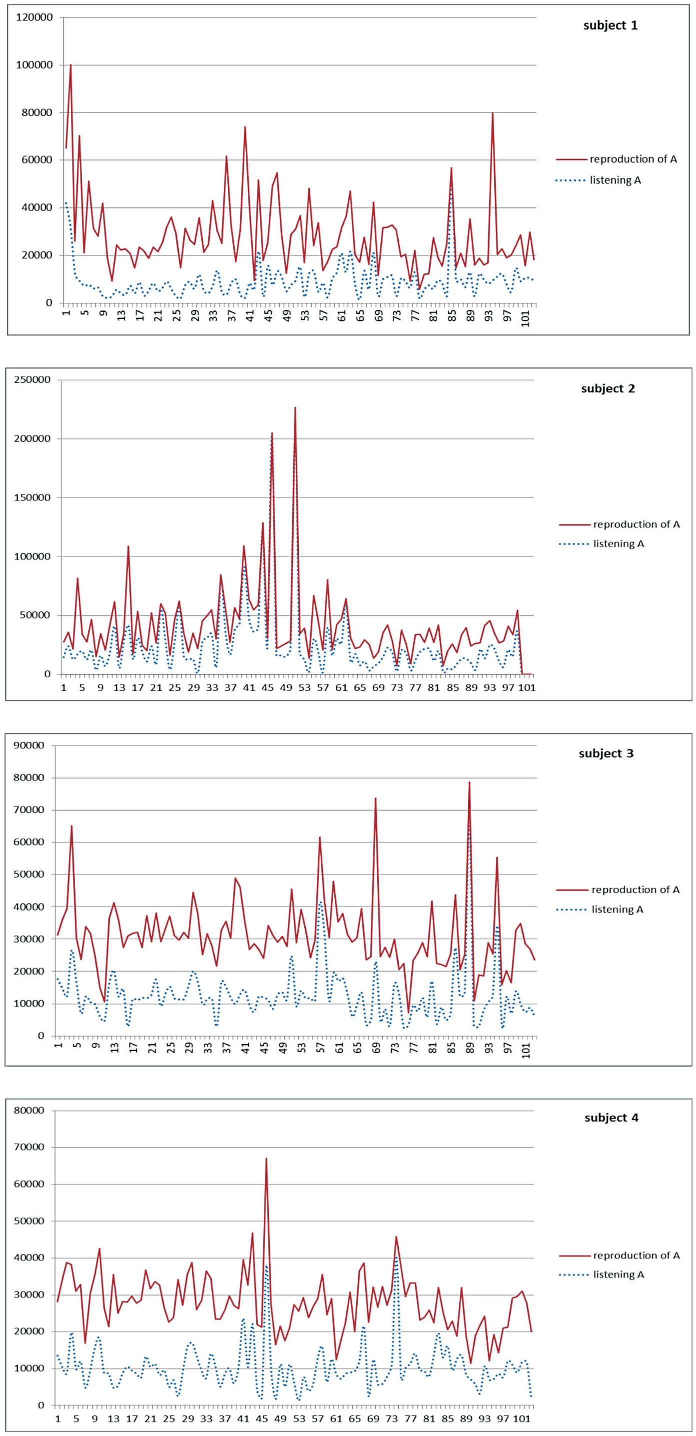

Fig. 3. Beta wave EEG diagrams while listening and reproducing note A (LA) for all subjects.

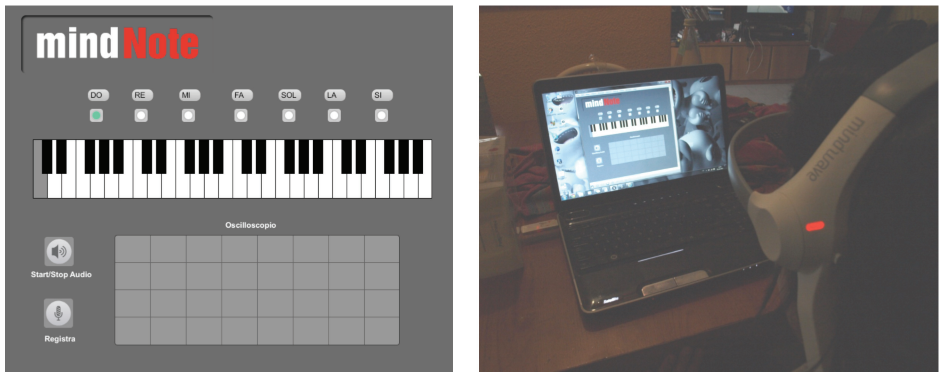

Fig. 4. A screenshot of the developed application; a user playing notes via the software application.

sounds, images, and gestures. Most users were able to reproduce from three to all the notes with the first use of the software.

In Figure 4, we show a screenshot of the application and a user playing notes using the software.

This work opens new scenarios for further developments, for example, to obtain complex melodies, but also for future research scenarios on human-computer interaction. Moreover, the combination paradigm used to guide users to reproduce the target sounds suggests many possible applications, not only in producing music but also in designing BCI-based games that involve active participation by users and audio/visual stimuli provided by computers, for both entertainment and game-based rehabilitation.

Other possible future developments concern the use of an extension of Max—that is, Max for Live, for an interface with Ableton, to provide powerful software for music production. If these programs were to act cooperatively, it may be possible to create applications based on the BCI structured to create or modify existing sounds in music composition. The adoption of such an approach might enable researchers to apply the results to the visual field, thus leading to the creation of application software for the visual arts.

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