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Brain-Computer Music Interfacing (BCMI): From Basic Research to the Real World of Special Needs

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Abstract

This paper reports on the development of a proof-of-concept brain-computer music interfacing system (BCMI), which we built to be tested with a patient with Locked-in Syndrome at the Royal Hospital for Neuro-disability, in London. The system uses the Steady State Visual Evoked Potential (SSVEP) method, whereby targets are presented to a user on a computer monitor representing actions available to perform with the system. Each target is encoded by a flashing visual pattern reversing at a unique frequency. In order to make a selection, the user must direct her gaze at the target corresponding to the action she would like to perform. The patient grasped the concept quickly and rapidly demonstrated her skill at controlling the system with minimal practice. She was able to vary the intensity of her gaze, thus changing the amplitude of her EEG and vary the consequent musical parameters. We have proved the concept that such a BCMI system is cost-effective to build, viable, and useful. However, ergonomic and design aspects of the system require further refinement in order to make it more practical for clinical usage. For instance, the system at present requires a therapist to place individual electrodes and calibrate a user's response to each stimulus, which can be time consuming. A new version of the system will require just positioning of a headset and, due to advanced algorithms, will require no calibration.

Keywords
music medicine, music therapy, palliative care, arts medicine

Introduction

Brain-computer interfacing technology, or BCI, allows a person to control appliances by means of commands expressed by brain signals relayed using appropriate brain monitoring technology.[1] Brain-computer interfacing technology has great potential to enable persons with severe physical disability to participate actively in music-making activities.

We are interested in developing brain-computer music interfacing technology, or BCMI, aimed at special needs and music therapy, in particular for people with severe physical disability who have relatively preserved cognitive functions. Our research is motivated by the extremely limited opportunities for active participation in music making available for people with severe physical disability, despite advances in technology. For example, severe brain injury, spinal cord injury and Locked-in Syndrome result in weak, minimal, or no active movement, which therefore prevent the use of gesture-based devices. These patient groups are currently either excluded from music recreation and therapy or are left to engage in a less active manner through listening/receptive methods only.

Despite the achievements of the field of BCMI,[2-6] this technology has seldom been trialed with the sector of the population that would most benefit. The time is ripe to take this research out of the laboratory toward the real world of special needs.

In this paper we introduce a BCMI system that was designed to be tested with a patient with Locked-in Syndrome at the Royal Hospital for Neuro-disability, in London. This test was aimed at establishing how appealing and enjoyable might a BCMI be to such a patient and whether the level of complexity of the musical task we have been working with in the laboratory is suitable for the envisaged scenario or not. We also

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observed the dynamics of using such a system outside the laboratory with a view of gaining a better idea of the practical needs of hospital staff, therapists, carers, and patients. Suggestions and criticism from the music therapy staff of the hospital and the patient with respect to improvements and potential further developments were also collected.

This article begins by introducing the basics of BCI and follows with an introduction to approaches to BCI and BCMI designs, respectively. Then we introduce the architecture of our system, followed by a commentary on the experience we gained from working in the real world with a patient. This experience informs the next steps of our research, which is discussed at the conclusion.

The Electroencephalogram

Currently the most viable and practical method of measuring brain signals for BCI purposes is to read the electroencephalogram, abbreviated as EEG, with electrodes placed on the scalp.

Other methods include magnetoencephalography (MEG), positon emission tomography (PET), functional magnetic resonance imaging (fMRI) and functional near infra-red spectroscopy (fNIRS). In general these methods offer greater resolution in location of brain activity but have a much slower response in addition to being less portable and considerably more expensive than EEG.

The EEG expresses the overall activity of millions of neurons in the brain in terms of charge movement.[7] In the case of non-invasive EEG (see note 1), electrodes detect this summed activity when it reaches the scalp. This is a difficult signal to handle because it is extremely faint and is filtered by the membranes that separate the cortex from the skull, the skull and the scalp. This signal needs to be amplified significantly before analysis in order to be of any use for a BCI.

In BCI research, it is often assumed that: (*a*) there is information in the EEG that corresponds to different cognitive tasks or at least a function of some sort, (*b*) this information can be detected, and (*c*) users can be trained to produce EEG with such information voluntarily.

For a review of various methods to analyze the EEG, please refer to ref 8. In general, power spectrum analysis is the most commonly used method. In simple terms, it breaks the EEG signal into different frequency bands and reveals the distribution of power between them (Figure 1). This is useful because it is believed that specific distributions of power in the spectrum of the EEG can encode different cognitive behaviors.

As far as BCI systems are concerned, the most important frequency activity in the EEG spectrum lies below 40 Hz. There are 5, possibly 6, recognized bands of EEG activity below 40 Hz, also referred to as EEG rhythms, which are often associated with specific states of mind. For instance, the frequencies falling between 8 Hz and 13 Hz are referred to as alpha rhythms and are usually associated with a state of relaxed wakefulness. The exact boundaries of these bands are not so clearly defined and the meaning of these associations can be contentious.

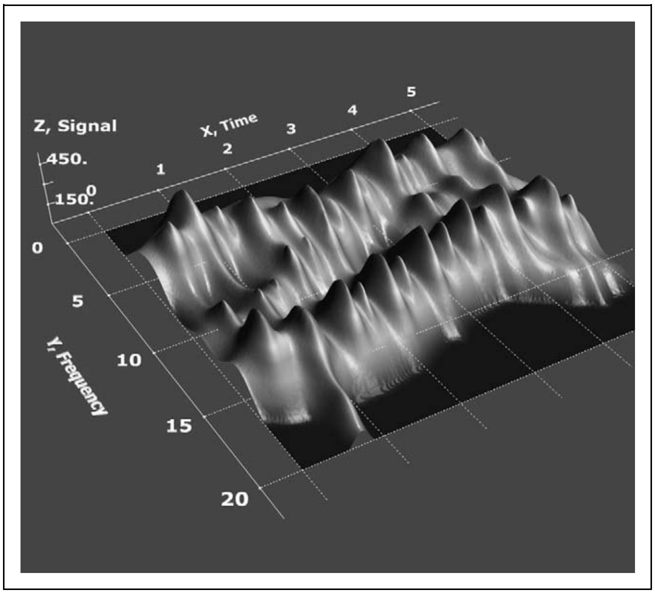

Figure 1. Spectrum analysis breaks the signal into different frequency bands (y coordinate) and reveals the distribution of power (z coordinate) between them in time (x coordinate). In this figure, the analysis revealed 2 prominent frequency bands in the regions of 5 Hz and 15 Hz, changing to 3 Hz and 12 Hz at approximately 3 seconds. (Source: ScienceGL, http://www.sciencegl.com, reprinted with permission.)

In practice, however, the actual meaning of the EEG rhythms is not crucial for a BCI system. What is crucial is to establish whether or not users can produce power within distinct frequency bands voluntarily. Obviously, such variations in the EEG need to be detected in order to be used as control signals. For instance, alpha rhythms are normally prominent in the EEG when the eyes are closed. This alone could be used as a form of control: by closing and opening the eyes, the user might be able to increase and decrease the power of the alpha rhythms at will.[3] This could be used, for example, to switch a device on (by closing the eyes to increase alpha power) or off (by opening the eyes to decrease alpha power) (see note 2).

Approaches to BCI

As already mentioned, the most important feature of a BCI is that which enables users to steer their EEG activity in one way or another. Broadly, there are 2 approaches to steering the EEG for a BCI: conscious effort and operant conditioning. Conscious effort induces changes in the EEG by engaging in specific cognitive tasks designed to produce specific EEG activity.[5,9] The cognitive task that is most often used in this case is motor imagery because it is possible to detect changes in the EEG of a subject imagining the movement of a limb; for example, left hand.[10] Other forms of imagery—such as auditory, visual, and navigation imagery—have been used, but relatively less often than motor imagery.

Operant conditioning involves the presentation of a task in conjunction with some form of feedback, which allows the user to develop unconscious control of the EEG. Once the brain is conditioned, the user is able to accomplish the task without being conscious of the EEG activity that needs to be generated.[11]

Somewhere in between the two aforementioned approaches is a paradigm referred to as evoked potentials, which is the paradigm we have adopted for our system.

Evoked potentials or event-related potentials (ERPs) occur from perception to an external stimulus or set of stimuli. Typically, ERPs can be evoked from auditory, visual, or tactile stimuli producing auditory (AEP), visual (VEP), and somato sensory (SSEP) evoked potentials, respectively. An ERP by definition is the electrophysiological response to a single event and therefore is problematic to detect in EEG on a single trial basis, becoming lost in the noise of on-going brain activity. However, if a user is subjected to repeated stimulation at short intervals (6 Hz–30 Hz), the brain's response to each subsequent stimulus is evoked before the response to the prior stimulus has terminated. Rather than being allowed to return to a baseline state, a so-called steady-state response is elicited.[12]

For users with healthy vision and eye movements the Steady State Visual Evoked Potential (SSVEP) is a robust paradigm for a BCI.[13] Typically, targets are presented to a user on a standard computer monitor representing actions available to perform with the BCI. This could be spelling words from an alphabet or selecting directions for a wheelchair to move, and so on. Each target is encoded by a flashing visual pattern reversing at a unique frequency; for example, 10 Hz. To make a selection users must simply direct their gaze at the target corresponding to the action they would like to perform. As the user's spotlight of attention falls over a particular target, the frequency of the unique pattern reversal rate can be accurately detected in the users EEG through basic spectral analysis.[14] Once empirical evidence of a subject's individual response is gathered, it is possible to classify not only a user's choice of target but also the extent to which the user is attending the target.[15] This gives scope for SSVEP BCIs where each target is not a simple binary switch but can represent an array of options depending on the user's attention. The SSVEP paradigm is extremely robust to interference from eye blinks and bodily movements and requires fairly little training to produce the required EEG activity accurately.

Approaches to Using EEG to Make Music

The notion of making music with the EEG emerged for the first time in the mid of the 1960s, when Alvin Lucier composed a piece entitled *Music for Solo Performer*. He placed electrodes on his own scalp, amplified the signals, and relayed them through loudspeakers that were "directly coupled to percussion instruments, including large gongs, cymbals, tympani, metal trash cans, cardboard boxes, bass and snare drums . . . ".[16] The characteristic low-frequency vibrations of the EEG emitted by the loudspeakers set the surfaces and membranes of the percussion instruments into vibration. In the early 1970s, David Rosenboom began systematic research into the potential of EEG to generate music, exploring the possibility of detecting aspects of our musical experience in the EEG signal.[17]

There have recently been a number of news stories in the press, reporting systems for anyone to control music with their brains (sic). The great majority of these systems, however, bear little relation to our research. We are concerned here with active voluntary control, whereas the great majority of those other systems provide no means for active control over the music they produce.

We identify 3 approaches to making music with EEG: *direct sonification, musification*, and *control*.

In direct sonification, the EEG signal is translated directly onto sound. The objective here is to "listen" to the EEG rather than (or in addition to) visualize EEG plotting. As an example, we cite the work of Hinterberger and Baier.[18] Also, the musical composition by Lucier mentioned above would fall in this category.[16]

In musification, the EEG signal is translated onto music by a system that generates musical sequences based on the behavior of the EEG. For instance, Miranda and his team developed a method to generate melodies from the topological behavior of the EEG across the electrodes on the scalp.[3] They assigned a musical note to each electrode and as the power of the EEG varied across the scalp, the system played the note that corresponded to the electrode that registered the highest power at specific moments.

In addition to artistic use, sonification, and to a certain extent musification, can be useful for scientific applications; for instance, to monitor the EEG aurally. But they are of little value for BCMI proper because in those cases the user does not actively control the music; it is a passive affair.

Conversely, in the *control* approach, the EEG signal is harnessed to control a musical system. Here the subject intentionally produces specific EEG patterns, which are detected by the system in order to control musical software.

Brain-Computer Music Interfacing System

Our BCMI system comprises 4 main modules: EEG Detection, EEG Analysis, Music Engine, and Stimuli/Visual Feedback Engine (Figure 2). Figure 3 shows a photograph of a subject using the system in the laboratory. The monitor on the left-hand side in Figure 3 shows 4 icons displayed by the Stimuli Engine. These icons flash at different frequencies (normally between 8 Hz and 16 Hz), reversing their colors. Each icon is associated with a musical process executed by the Music Engine module. Therefore, the Music Engine can execute 4 types of processes, which the user can select by staring at the respective flashing icon. The EEG Detection module is constantly scanning the EEG of the subject and feeding the EEG analysis module, which is, in turn, constantly analyzing the signal online.

The system requires just 3 electrodes: a bipolar pair and a ground electrode. We used active electrodes (see note 3) and impedances were kept below 5Ω by parting hair at openings in electrode cap and using conductive gel. This are widely practiced standard BCI techniques.

As a hypothetical example, let us suppose that the top icon of the Stimuli Engine (plus sign) is associated with the task of

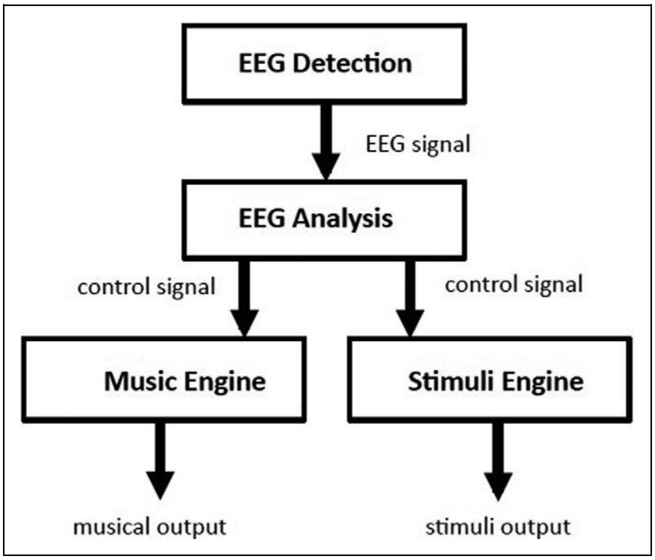

Figure 2. The components of the brain-computer music interfacing system (BCMI) system.

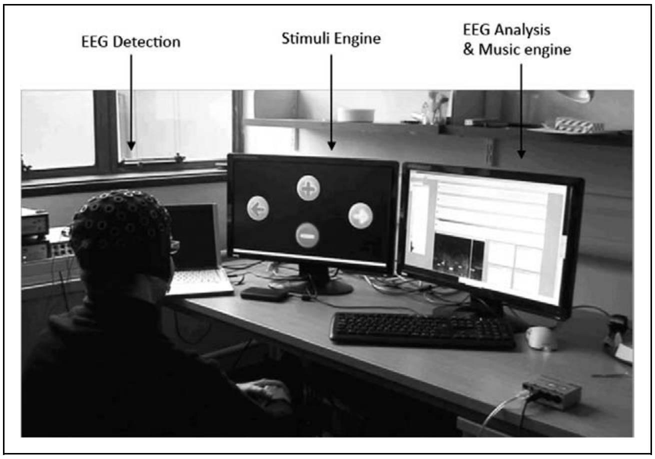

Figure 3. Photograph of a participant operating the system in the laboratory.

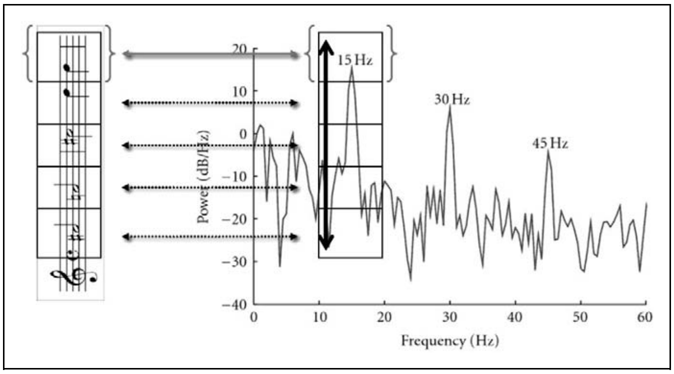

Figure 4. Five bandwidths are established for the varying control signal, which are associated to the indices of an array of musical notes.

generating a melody from an ordered set of 5 notes. Let us say that this icon flashes at a rate of 15 Hz. When one stares at it, the EEG Analysis module detects that the subject is staring at this icon and sends a command to the Music Engine module to generate the respective melody. The more the subject attends to this icon, the more prominent the magnitude of the brain's SSVEP response to this stimulus. This produces a varying control signal, which is used by the Music Engine to produce the melody and by the Stimuli Engine to provide a visual feedback to the user: the size of the icon increases or decreases as a function of this control signal.

The Music Engine module uses the control signal to generate the melody in a variety of ways, which can be customized. For the sake of clarity, only one of the simplest methods is introduced here.

A sequence of five musical notes is stored in an array, whose index varies from 1 to 5. By sliding the index up and down, one can play the notes in sequence (index going up) or in reverse (index going down). Five bandwidths of power are established for the varying control signal, each of which corresponding to an index value of the array of musical notes. As the signal varies within these bandwidths, the corresponding indices trigger the respective musical notes stored in the array (Figure 4). In this way, users can steer the production of the notes by the intensity to which they attend to the icon. One can bring the index down by looking away and bring the index up by staring at it again. Fine control of this variation can be achieved with practice; for example, to repeat a single note many times, or repeat a subgroup of notes, and so on.

This method has proved successful because one can almost immediately produce musical notes with very little, or no training, simply by looking intently at the different icons of the Stimuli Engine, as if playing a piano by depressing its keys at will. As one learns to modulate the extent to which s/he is attending the icons, more sophisticated musical control can be achieved, as if learning to play a musical instrument: the more one practices the better one becomes at it.

Toward the Real Word: Benefits and Challenges

For people who have acquired complex physical disabilities as a result of, for example, spinal cord injury, severe brain injury, or Locked-in Syndrome, overcoming physical barriers within the environment to gain control over one's life is a moment-to-moment challenge. Increasing the locus of control for people with severely limited movement is most frequently achieved by a combination of environmental adaptation and the use of technological aids. Realizing musical expression for professional, recreational, or therapeutic purposes in these situations typically relies on alternative interfaces in combination with switch-accessible music software. However, the range of devices and adaptive software that is commercially available has not yet met the challenge of those with very complex needs. Even devices requiring only minimal movements can cause physical fatigue due to the need for repetitive

Figure 5. Tester M trialing the system. The icon on the left-hand side is slightly larger than the others because she was attending to this icon at the moment this photograph was taken.

movements or maintaining a physical posture, which enables access to and manipulation of such devices for a period of time. Thus, technology that reads brain signals draws on an individual's residual strengths and so is highly suited to people with full cognitive functioning. The control of the musical output with a BCMI often requires training, thus "playing" music in this way requires skill and learning, much like learning to play a musical instrument. This can be an attractive attribute for many individuals.

Enabling an individual to have active control must remain central to the experience of music-making. Similarly, generating musical output needs to be genuinely expressive experience rather than merely a selection of choices from pre-programmed drop-down menus. However, the benefits for applying such tools following acquired injury include maintaining occupation and opening doors for engaging in rehabilitation programs. The effects should not be underestimated; opportunities for engaging in activities of interest require enormous reconfiguration following severe injury.

An initial trial of the system was conducted with an adult female with Locked-in Syndrome (henceforth called "Tester M") whose only active movements following a stroke include eye movements, facial gestures, and minimal head movements. She retains full cognitive capacity. Tester M trialled the system during a 2-hour session. This is a considerable period of time for someone undergoing rehabilitation after acquiring such severe disabilities. Being familiar with eye gaze technology for her alternative communication system, Tester M grasped the SSVEP concept quickly and rapidly demonstrated her skill at playing the system with minimal practice (Figure 5). The speed at which she mastered the system was considerably less than that of able-bodied staff present who also tried the system. She was able to vary the intensity of her gaze at will, thus changing the amplitude of her EEG and vary the consequent melodic and dynamic output. The participant had success in copying notes played on a piano by an assistant and then playing an independent melodic line to a looped background track. Response times of both musical and visual feedback event is dependent on how much SSVEP from each target resides in the buffer and thus is a dynamic system in relation to gaze. Minimum response times for this participant between attending a target and the feedback event were approximately 1 to 2 seconds.

Personal correspondence with Tester M following this trial communicated that she had enjoyed considerably using the system and that "... it was great to be in control again." This feedback is promising and supports the proposition that the system is appealing to people with such complex needs. The possibilities for applying the system within group settings is immediately apparent and an exciting prospect for people with limited opportunities for participating as an equal partner in group ventures.

Some aspects of the system require further refinement to make it more viable for clinical application. The frequency rate at which the icons flash may limit using the system with people known to have photosensitive epilepsy, a common consequence following acquired brain injury. Other minor discomforts or aesthetic concerns about wearing the skull cap may be unattractive for people who are already managing issues concerning self-image following acquired disability. The skills required of the therapist in calibrating the system are outside typical clinical skills. Although the skills factor can be overcome with relatively minimal training, lacking knowledge and skills and increasing the time burden of a clinical load are all known to be preventative factors influencing the uptake of technology in clinical practice.[19,20] Lastly, although an initial trial in the clinical setting is promising, it is important to ensure that the system offers an adequate musical repertoire or challenge to maintain the engagement of people who may have vastly sophisticated musical experiences and tastes. In this trial, the "Lounge" musical genre employed would be attractive to a wide age range: other popular genres with wide applicability include Latin, Reggae, and Jazz. Optimizing options for choice is an important feature and meets the need to either increase or minimize the level of musical complexity accordingly.

Concluding Remarks

This article presented a BCMI adopting the SSVEP paradigm in a way that has not been used before. Importantly, our BCMI is very affordable to build: it requires a laptop computer, related software, 3 electrodes, and an EEG amplifier (see note 4). These amount to under $3500. Placement of electrodes typically takes less than 15 minutes and is non-complex.

Our system uses a unique method of harnessing techniques of capturing brain information to be mapped onto a musical system for creative musical expression. Crucially here, the data received is not only being monitored but carefully translated through algorithmic analysis and optimized creating a biofeedback system between the user and the music generated.

We have demonstrated that the scientific and technological methods employed in developing a BCMI can successfully translate out of the laboratory and into the real world. It is in this transition where the focus is shifted away from the challenges of the technology and toward the requirements and ideas of professional therapists, which can be implemented back in the laboratory. The most important aspect of this precise level of control on offer, in a musical system, is the ability to provide instantaneous audible feedback to the patient, again, akin to that of an acoustic instrument, a factor taken for granted by users with physical abilities.

In order to make the most of BCMI technology in the real world, progress needs to be made in order for a system to become portable and easy to maintain. Multiple cables, computer monitors, and high levels of configuration associated with high-end customized BCMI systems needs to be compacted and transferred to a more accessible platform. Not only is this goal practical for the busy schedules of practitioners, a system such as this would simply be more appealing to patients and to staff, as it would cement the belief that expert knowledge need not be required to run it.

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Notes

1. Non-invasive EEG uses electrodes placed on the scalp whereas invasive EEG uses electrodes placed underneath the scalp, directly onto the cortex. For obvious health and safety reasons, the latter is rarely used in BCI.
2. This simplistic example is given here only as a hypothetical illustration. In reality, this is not so trivial.
3. Provided by g.Tec, Austria: http://www.gtec.at/.
4. We have used the WaveRider Pro 4-channel amplifier, which allows for use by up to 4 subjects simultaneously. This costs $1,700. The same manufacturer also provides a 2-channel amplifier for $995. Website: www.mindpeak.com (Last assessed on 04 January 2011). The photograph in Figure 3 shows two computer monitors. These are optional; they were used here only for software development and tests in the laboratory. The monitor of the laptop only is sufficient (Figure 5).

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Bios

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