GENERAL ARTICLE

Interfacing the Brain Directly with Musical Systems: On Developing Systems for Making Music with Brain Signals

Eduardo Reck Miranda and Andrew Brouse

ABSTRACT

The authors discuss their work on developing technology to interface the brain directly with music systems, a field of research generally known as Brain-Computer Interfacing (BCI). The paper gives a brief background of BCI in general and surveys various attempts at musical BCI, or Brain-Computer Music Interface (BCMI)—systems designed to make music from brain signals, or *brainwaves*. The authors present a technical introduction to the electroencephalogram (EEG), which measures brainwaves detected by electrodes placed directly on the scalp. They introduce approaches to the design of BCI and BCMI systems and present two case study systems of their own design: the BCMI-Piano and the Inter-Harmonium.

There is a growing number of researchers worldwide working in the field of Brain-Computer Interfacing (BCI). Our work is unique, however, in that we are focused on the development of BCI systems for musical applications and we pay special attention to the development of generative music techniques tailored for such systems. We might call such systems Brain-Computer Music Interfaces (BCMIs). We should clarify that the BCI research community understands a BCI as a system that allows for the control of a machine by thinking about the task in question; e.g. controlling a robotic arm by thinking explicitly about moving an arm. This is an extremely difficult problem. The BCMI-Piano and the Inter-Harmonium presented in this paper do not employ this type of explicit control. We are not primarily interested in a system that plays a melody by thinking the melody itself; rather, we are furnishing our systems with artificial intelligence so that they can perform their own interpretations of the meanings of EEG patterns. Such machine interpretations may not always be accurate or realistic, but this is the type of human-computer interaction that we wish to address in our work.

To date, most efforts in BCI research have been aimed at developing assistive technology to help disabled people communicate or control mechanical devices (such as wheelchairs or prosthetic limbs). Comparatively little has been done to implement BCI technology for musical applications.

Making Music with Brainwaves

Human brainwaves were first measured in 1924 by Hans Berger [1,2]. Today, the electroencephalogram (EEG) has become one of the most useful tools in the diagnosis of epilepsy and other neurological disorders. The fact that a machine can read signals from the brain has sparked the imaginations of scientists, artists and researchers. Consequently, the EEG has made its way into a myriad of applications.

In the early 1970s, Jacques Vidal took the first tentative step toward a BCI system. The results of this work were published in 1973 [3]. Recently Vidal has revisited this field in his speculative article "Cyberspace Bionics" [4]. Many other interesting attempts followed Vidal's work. In 1990, for example, Jonathan Wolpaw and colleagues developed a system to allow primitive control of a computer cursor by individuals with severe motor deficits. Users were trained to use aspects of their 8–13 Hz alpha rhythm to move the cursor in simple ways [5]. In 1998, Christoph Guger and Gert Pfurtscheller presented a paper reporting an impressive advance in BCI research: an EEG-based system for controlling a prosthetic hand [6]. More recent reports on BCI research have been published [7].

As early as 1934, a paper in the journal *Brain* reported a method for listening to the EEG [8], but it is now generally accepted that it was composer Alvin Lucier who, in 1965, com-

Fig. 1. Brainwaves can be detected by placing electrodes on the scalp. (© Eduardo Reck Miranda)

Eduardo Reck Miranda (composer, researcher, teacher), Computer Music Research, School of Computing, Communications and Electronics, University of Plymouth, Drake Circus, Plymouth, Devon PL4 8AA, U.K. E-mail: <eduardo.miranda@plymouth.ac.uk>.

Andrew Brouse (composer, researcher, teacher), Computer Music Research, School of Computing, Communications and Electronics, University of Plymouth, Drake Circus, Plymouth, Devon PL4 8AA, U.K. E-mail: <andrew.brouse@plymouth.ac.uk>.

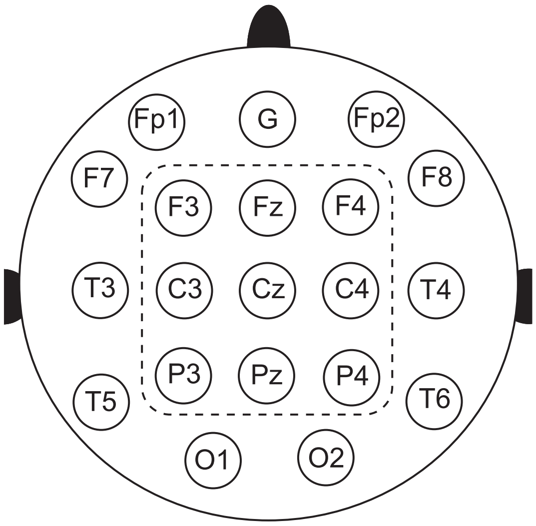


Fig. 2. The standard 10-20 Electrode Placement System; the electrodes are placed at positions measured at 10% and 20% of the head circumference. (© Eduardo Reck Miranda)

posed the first musical piece using the EEG: *Music for Solo Performer* [9]. This was a piece for percussion instruments made to resonate by the performer's EEG waves. Later in the 1960s, Richard Teitelbaum used the EEG (and other biological signals) to control electronic synthesizers [10]. Then, in the early 1970s, David Rosenboom began systematic research into the potential of the EEG to generate artworks, including music [11]. He developed EEG-based musical interfaces associated with a number of compositional and performance environments exploring the hypothesis that it might be possible to detect certain aspects of our musical experience in the EEG signal [12].

Since the 1970s, many other musicians have experimented with EEG signals to make music, but the field has advanced slowly. In 2003, one of the current authors, Eduardo Miranda, and colleagues published a paper in *Computer Music Journal* [13] reporting on experiments and techniques for enhancing the EEG signal and training the computer to identify EEG patterns associated with simple cognitive musical tasks.

THE ELECTROENCEPHALOGRAM (EEG)

Neural activity generates electric fields that can be recorded with electrodes attached to the scalp (Fig. 1). The electroencephalogram, or EEG, is the visual plotting of this signal. In current usage, the initials commonly refer to both the method of measurement and the electric fields themselves. These electric fields are extremely faint, with amplitudes in the order of only a few microvolts. These signals must be greatly amplified in order to be displayed and/or processed [14,15].

The EEG is measured as the voltage difference between two or more electrodes on the surface of the scalp, one of which is taken as a reference. There are basically two conventions for positioning the electrodes on the scalp: the *10-20 Electrode Placement System* (as recommended by the International Federation of Societies for EEG and Clinical Neurophysiology) and the *Geodesic Sensor Net* (developed by a firm called Electric Geodesics [16]). The former is more popular and is the convention adopted for the systems described in this paper: It uses electrodes placed at positions that are measured at 10% and 20% of the head circumference (Fig. 2). In this case, the terminology for referring to the position of the electrodes uses a key letter that indicates a region on the scalp, and a number: F = frontal, Fp = frontopolar, C = central, T = temporal, P = parietal, O = occipital and A = auricular (the earlobe, not shown in Fig. 2). Odd numbers indicate electrodes on the left side of the head and even numbers those on the right side.

The set of electrodes being recorded at one time is called a *montage*. Montages fall into one of two categories: *referential* or *bipolar*. In referential montages, the reference for each electrode is in common with other electrodes; for example, each electrode may be referenced to an electrode placed on the earlobe. An average reference means that each electrode is compared to the average potential of every electrode. In bipolar montages, each channel is composed of two neighboring electrodes; for example, channel 1 could be composed of Fp1-F3, where Fp1 is the active electrode and F3 is the reference; channel 2 could then be composed of Fp2-F4, where Fp2 is the active electrode and F4 is the reference; and so forth.

The EEG expresses the overall activity of millions of neurons in the brain in terms of charge movement, but the electrodes can detect this only in the most superficial regions of the cerebral cortex. The EEG is a difficult signal to handle because it is filtered by the meninges (the membranes that separate the cortex from the skull), the skull and the scalp before it reaches the electrodes. Furthermore, the signals arriving at the electrodes are integrated sums of signals arising from many possible sources, including artifacts such as the heartbeat and eye blinks. This signal needs to be further scrutinized with signal processing and analysis techniques in order to be of any use for our research.

There are a number of approaches to quantitative EEG analysis, such as *power spectrum*, *spectral centroid*, *Hjorth*, *event-related potential (ERP)* and *correlation*, to cite but five. A brief nonmathematical introduction to EEG power spectrum, spectral centroid and Hjorth analyses is given below because of their relevance to the systems introduced in this paper. We take note of discussions of other analysis techniques and how they have been used in the neuroscience of music research [17–21].

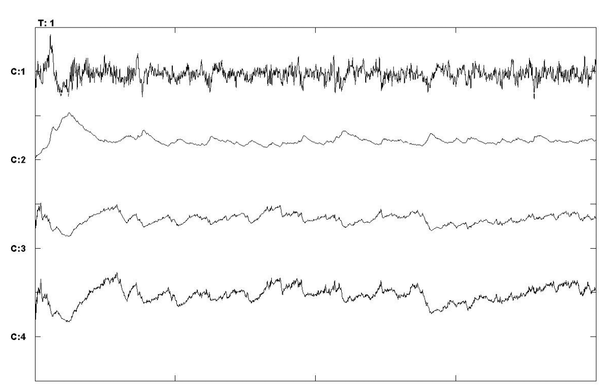


Fig. 3. An example of Hjorth analysis. (© Eduardo Reck Miranda) A raw EEG signal is plotted at the top (C:1) and its respective Hjorth analysis is plotted below: activity (C:2), mobility (C:3) and complexity (C:4).

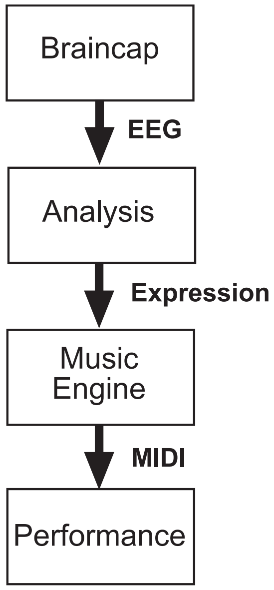


Fig. 4. The BCMI-Piano is composed of four modules. (© Eduardo Reck Miranda)

Power Spectrum Analysis

Power spectrum analysis is based upon techniques of Fourier analysis, such as the Discrete Fourier Transform (DFT). DFT, sometimes called the finite Fourier transform, is a mathematical method widely employed in signal processing and related fields to analyze the frequencies contained in the spectrum of a signal. This is useful because the distribution of power in the spectrum of the EEG can reflect certain states of mind. For example, a spectrum with salient low-frequency components can be associated with a state of drowsiness, whereas a spectrum with salient high-frequency components could be associated with a state of alertness. There are five commonly recognized frequency bands or rhythms of EEG activity, each with its specific associated mental states: *delta*, *theta*, *alpha*, *low beta* and *high beta*. There is, however, some controversy as to the exact frequency boundaries of these bands and about the mental states with which they are associated.

Related to power spectrum analysis is *spectral centroid* analysis, which calculates the spectral "center of gravity" of the signal, that is, the midpoint of its energy distribution. Spectral centroid is a measure of the average frequency weighted by amplitude, usually averaged over time.

Hjorth Analysis

Hjorth introduced an interesting method for clinical EEG analysis [22] that measures three attributes of the signal: its *activity*, *mobility* and *complexity*. Essentially, this is a time-based signal analysis. This method is interesting because it represents each time step (or window) using only these three attributes and this is done without conventional frequency domain description (such as that of DFT).

The signal is measured for successive epochs (or windows) of one to several seconds. Two of the attributes are obtained from the first and second time derivatives of the amplitude fluctuations in the signal. The first derivative is the rate of change of the signal's amplitude. At peaks and troughs the first derivative is zero. At other points it will be positive or negative depending on whether the amplitude is increasing or decreasing with time. The steeper the slope of the wave is, the greater the amplitude of the first derivative. The second derivative is determined by taking the first derivative of the first derivative of the signal. Peaks and troughs in the first derivative, which correspond to points of greatest slope in the original signal, result in zero amplitude in the second derivative, and so forth.

Activity is the variance of the amplitude fluctuations in the epoch. Mobility is calculated by taking the square root of the variance of the first derivative divided by the variance of the primary signal. Complexity is the ratio of the mobility of the first derivative of the signal to the mobility of the signal itself. A sine wave has a complexity of one.

There is one fact, however, that should be borne in mind with Hjorth analysis: It does not produce very clear results if the input signal has more than one strong band of frequencies in the power spectrum. This problem can be alleviated by band-pass filtering the signal beforehand, but this may cause some loss of information. A band-pass filter is a device that lets through frequencies between two other given frequencies.

Figure 3 shows an example of Hjorth analysis. There is no clear agreement as to what these measurements mean in terms of mental states. It is common sense to assume that the longer a subject remains focused on a specific mental task, the more stable the signal is, and therefore the lower the variance of the amplitude fluctuation. However, this assumption does not address the possible effects of fatigue, habituation and boredom, which we have not yet accounted for in our research.

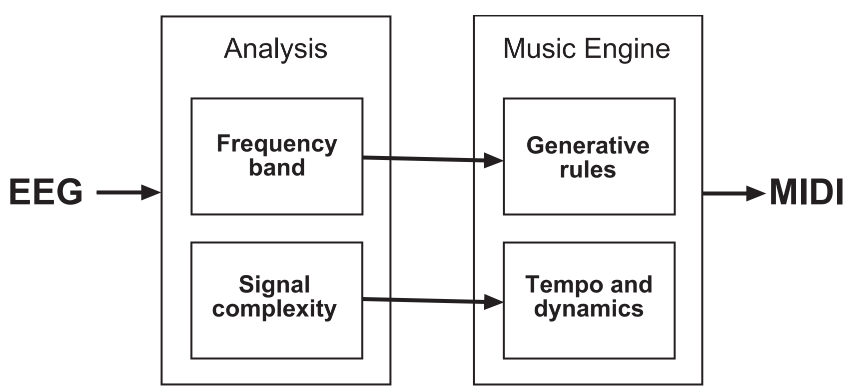
Approaches to BCI System Design

Generally speaking, a BCI is a system that allows one to interact with a computing device by means of signals emanating directly from the brain. There are two basic ways of tapping brain signals: *invasive* and *noninvasive*. Whereas invasive methods require the placement of sensors connected to the brain inside the skull, noninvasive methods use sensors that can read brain signals from outside the skull. Invasive technology is becoming increasingly sophisticated, but brain prosthetics is not a viable option for this research. The most viable noninvasive option for tapping the brain for BCI is currently the EEG.

It is possible to identify three categories of BCI systems:

1. User oriented: BCI systems in which the computer adapts to the user. Metaphorically speaking, these systems attempt to read the EEG of the user in order to control a device. For example, Anderson and Sijercic [23] reported on the development of a BCI that learns how to associate specific EEG patterns

Fig. 5. Spectral information is used to activate generative music rules to compose music on the fly, and the signal complexity is used to control the tempo of the music. (© Eduardo Reck Miranda)



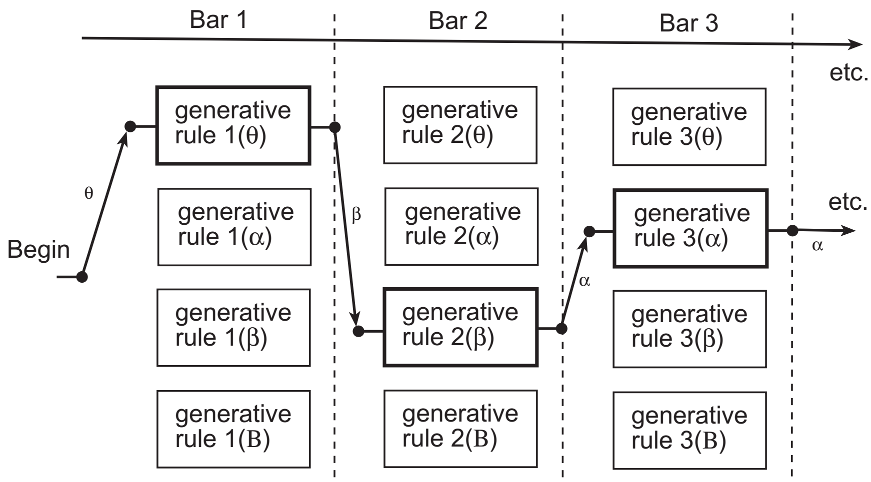


Fig. 6. Each bar of a composition is produced by one of four possible generative rules, according to the EEG rhythm of the subject. (© Eduardo Reck Miranda)

from a subject with commands for navigating a wheelchair.

2. Computer oriented: BCI systems in which the user adapts to the computer. These systems rely on the capacity of the users to learn to control specific aspects of their EEGs, affording them the ability to exert some control over events in their environments. Examples have been shown where subjects learn how to steer their EEG to select letters for writing words on a computer screen [24].
3. Mutually oriented: BCI systems that combine the functionalities of both categories; the user and computer adapt to each other. The combined use of mental task pattern classification and biofeedback-assisted online learning allows the computer and the user to adapt. Prototype systems to move a cursor on the computer screen have been developed in this fashion [25,26].

Until recently, those who have attempted to employ EEG as part of a music controller have done so by associating certain EEG characteristics, such as the power of the EEG alpha rhythms, with specific musical actions. These are essentially computer-oriented systems, as they require users to learn to control their EEGs in certain ways.

THE BCMI-PIANO

The BCMI-Piano falls into the category of computer-oriented systems. The motivation for this system, however, departs from a slightly different angle than do other BCI systems. We aimed for a system that would make music by "guessing" what might be going on in the mind of the subject rather than a system for explicit control of music by the subject. Learning to steer the system by means of biofeedback would be possible, but we are still investigating whether this possibility would produce effective control.

We acknowledge that the notion of "guessing the mind" here is extremely simplistic, but it is plausible: It is based on the assumption that physiological information can be associated with specific mental activities [27].

The system is programmed to look for information in the EEG signal and match the findings with assigned generative musical processes. For example, if the system detects prominent alpha rhythms in the EEG, then it will generate musical passages associated with the alpha rhythms. These associations are predefined and they determine the different types of music that are generated in association with different mental states.

The system is composed of four main modules (Fig. 4): *braincap*, *analysis*, *music engine* and *performance*. The brain signals are sensed with 7 pairs of gold EEG electrodes on the scalp, roughly forming a circle around the head (bipolar montage): G-Fz, F7-F3, T3-C3, O1-P3, O2-P4, T4-C4, F8-F4. A discussion of the rationale of this configuration falls outside the scope of this paper. It suffices to say that we are not looking for signals emanating from specific cortical sites; rather, the idea is to sense the EEG behavior over the whole surface of the cortex. The electrodes are plugged into a real-time biosignal acquisition system manufactured by g.Tec (Guger Technologies) [28].

The analysis module is programmed in Matlab and Simulink [29]. It generates two streams of control parameters. One stream contains information about the most prominent frequency band in the signal and is used by the music engine to compose the music. The other stream contains information about the complexity of the signal and is used by the music engine to control the tempo of the music (Fig. 5).

The core of the music engine module is a set of generative music rules, each of which produces a musical bar, or measure. A composition is then constructed out of a sequence of musical bars (Fig. 6). For each bar there are four possible generative rules, each of which is associated with one of four EEG rhythms: theta, alpha, low beta, high beta. For example, 96 generative rules would be required to compose a piece lasting for 24 bars. The system works as follows: every time it has to produce a bar, it checks the power spectrum of the EEG at that moment and activates one of the four generative rules associated with the most prominent EEG rhythm in the signal. The system is initialized with a reference tempo (e.g. 120 beats per minute) that is constantly modulated by the signal complexity analysis (i.e. Hjorth analysis). A detailed explanation of the generative rules is beyond the scope of this paper.

THE INTERHARMONIUM

The InterHarmonium was conceived as a networked live brainwave music performance system [30]. The initial impetus was to allow geographically separated performers to simultaneously play musical compositions with their brainwaves. As with the BCMI-Piano, the motivation for this system springs from a source other than prosthetic or therapeutically oriented BCI systems. The InterHarmonium was envisioned as a platform for artistic explorations into the topographies of computer networks as a metaphor for our own central nervous systems: Whereas the brain is formed of billions of "networked" neurons, the InterHarmonium is formed of various networked brains. Although it uses analysis techniques similar to proper BCI systems, the InterHarmonium would more appropriately be considered a form of "auditory display" [31], as it is attempting to present real-time brainwave activity in such a way as to make it intuitively and immediately comprehensible to listeners. The fact that multiple networked brains in different places can control music in other, geographically separated locations is intrinsic to the InterHarmonium design and central to its aesthetic proposition.

Figure 7 illustrates the general structure of the system. In short, brain signals are sensed, digitized and properly converted to a suitable format to then be sent over standard Internet Protocol networks by the InterHarmonium servers; these servers function as brainwave sources. The InterHarmonium client computers function as brainwave sinks, as well as brainwave analysis and sound synthesis nodes. The nodes can all have either all the same or their own unique sets of sonification rules.

The EEG was sensed using 4–8 electrodes on the performer's head with a ground on one ear. The electrodes were positioned on either one or both hemispheres of the skull, roughly corresponding to the frontal (Fp1, Fp2), temporal (T3, T4), occipital (O1, O2) and parietal (P3, P4) lobes. The earlobe electrode (A) was used to improve common-mode noise rejection. Differential measurements were made between electrodes of the same hemisphere. The electrodes were plugged into a 16-channel Grass model 8-18 D analog EEG machine [32].

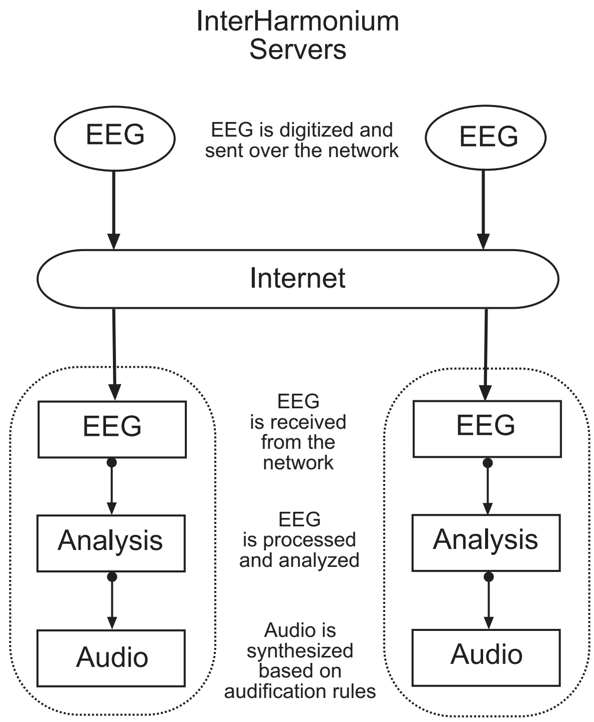


Fig. 7. The structure of the InterHarmonium system. (© Eduardo Reck Miranda)

The amplified EEG signal from the Grass machine was digitized using a Mark of the Unicorn 828 8-channel A-D audio interface [33]. Many current high-quality audio interfaces such as this have usable response down to 1 Hz or lower, which is suitable for digitizing most EEG signals. The software was implemented in Max/MSP [34], using the OpenSoundControl (OSC) protocol [35] to format the data and the UDP protocol to transport it over the Internet.

Brainwave analysis and sound synthesis takes place at the client end. In contrast to the BCMI-Piano described above, the InterHarmonium does not involve any high-level compositional processes: it sonifies the incoming EEG data according to chosen parameters.

The sound synthesis process is inspired by a well-known psychoacoustic phenomenon known as the "missing fundamental." Most musical instruments produce a fundamental frequency plus several higher tones, which are whole-number multiples of the fundamental. The beat frequencies between the successive harmonics constitute subjective tones that are at the same frequency as the fundamental and therefore reinforce the sense of pitch of the fundamental note being played. If the lower harmonics are not produced because of poor fidelity or filtering of the sound reproduction equipment, one still can hear the tone as having the pitch of the nonexistent fundamental because of the presence of these beat frequencies. This "missing fundamental" effect plays an important role in sound reproduction by preserving the sense of pitch (including the perception of melody) when reproduced sound loses some of its lower frequencies.

The vast majority of spectral energy in the human EEG typically lies below 30 Hz and thus largely below the range of normal human perception. The idea is that if one can synthesize the corresponding harmonic overtone structure of a given subsonic frequency (such as the 8–13 Hz alpha), then the psychoacoustic phenomenon of the missing fundamental will make the listener aware of that frequency although he or she may not actually be able to hear it.

This was done by calculating the ongoing spectral centroid averaged over all brainwave signals and using that as the "fundamental" for the synthesized sound (most likely a subsonic tone); then overtones or harmonic partials —whole-number frequency multiples— were calculated in the audible range. The amplitude of the various partials was controlled based on calculations derived from relationships between the ongoing brainwave signals. The harmonic center of the fundamental was derived from the spectral centroid and the shifting timbral surface textures were based on the moment-to-moment changes in relationships between different channels of the performer's EEG.

Discussion and Concluding Remarks

Our research work in this area owes a historical debt to the pioneering work of people such as David Rosenboom, Richard Teitelbaum and Alvin Lucier, but extends those earlier experiments with new possibilities for much finer granularity of control over real-time musical processes.

The work presented in this paper is the result of intense multidisciplinary research, ranging from neuroscience and medical engineering to music technology and composition. While we have a good understanding of the compositional requirements of music as well as the technical exigencies in the implementation of BCMI, we acknowledge that our research so far has revealed only the tip of a vast iceberg. There still remain a number of cumbersome problems to be resolved before we can realize our ultimate goal: an affordable, flexible and practically feasible BCMI for composition and performance with intelligent real-time computer music systems.

Although powerful mathematical tools for analyzing the EEG already exist, we still lack a good understanding of their analytical semantics in relation to musical cognition. However, continual progress in the field of cognitive neuroscience [36] is improving this scenario substantially. Once these issues are better understood we will be able to program our devices to recognize patterns of cognitive activity in the brainwaves and activate appropriate musical algorithms associated with such patterns. Preliminary work in this regard has been reported in a recent paper [37].

Other aspects that need to be developed include the nonergonomic nature of the electrode technology for sensing the EEG, which can be uncomfortable and awkward to wear. There are certainly possibilities for innovations in the hardware design of EEG capture devices. In his original 1973 paper, Jacques Vidal suggested putting miniature preamplifiers right at the site of the electrode. Inexpensive auto-scanning/autonegotiating wireless chips are now available and could be placed on the head along with small preamplifiers and microprocessors. It would thus be possible to build a wearable EEG sensor device with built-in amplifiers, signal processing and wireless data transmission [38].

References and Notes

1. H. Berger, "Über Das Elektrenkephalogramm Des Menschen," *Archiv für Psychiatrie und Nervenkrankheiten* **87** (1929) pp. 527–570.

2. H. Berger, "On the Electroencephalogram of Man," *The Fourteen Original Reports on the Human Electroencephalogram, Electroencephalography and Clinical Neurophysiology*, Supplement No. 28 (Amsterdam: Elsevier, 1969).

3. J.J. Vidal (1973), "Toward Direct Brain-Computer Communication," in L.J. Mullins, ed., *Annual Review of Biophysics and Bioengineering* (Palo Alto, CA: Annual Reviews, 1993) pp. 157–180.

4. J.J. Vidal, "Cyberspace Bionics" <http://www.cs.ucla.edu/~vidal/bionics.html>. Accessed 17 June 2004.

5. J. Wolpaw et al., "An EEG-Based Brain-Computer Interface for Cursor Control," *Electroencephalography and Clinical Neurophysiology* **78**, No. 3, 252–259 (1991).

6. C. Guger and G. Pfurtscheller, "EEG-Based Brain-Computer Interface (BCI) Running in Real-Time under Windows," *Electroencephalography and Clinical Neurophysiology (Proceedings of 9th European Congress of Clinical Neurophysiology)* **106**, Supplement 1, 91–100 (1998).

7. For recent reports on BCI research please refer to the special issue of *IEEE Transactions on Biomedical Engineering* **51** (June 2004).

8. E. Adrian and B. Matthews, "The Berger Rhythm: Potential Changes from the Occipital Lobes in Man," *Brain* **57**, No. 4, 355–385 (1934).

9. A. Lucier, "Statement On: Music for Solo Performer," in D. Rosenboom, ed., *Biofeedback and the Arts: Results of Early Experiments* (Vancouver, Canada: Aesthetic Research Centre of Canada, 1976).

10. R. Teitelbaum, "In Tune: Some Early Experiments in Biofeedback Music (1966–1974)," in D. Rosenboom [9].

11. D. Rosenboom, *Extended Musical Interface with the Human Nervous System*, Leonardo Monograph Series No. 1 (Berkeley, CA: International Society for the Arts, Sciences and Technology, 1990).

12. D. Rosenboom, "The Performing Brain," *Computer Music Journal* **14**, No. 1, 48–65 (1990).

13. E.R. Miranda et al., "On Harnessing the Electroencephalogram for the Musical Braincap," *Computer Music Journal* **27**, No. 2, 80–102 (2003).

14. E. Niedermeyer and F.H. Lopes da Silva, eds., *Electroencephalography,* 2nd Ed. (Munich, Germany: Urban and Schwartzenberg, 1987).

15. K.E. Misulis, *Essentials of Clinical Neurophysiology* (Boston, MA: Butterworth-Heinemann, 1997).

16. Electrical Geodesics, Inc. <http://www.egi.com/>. Accessed 21 June 2004.

17. M. Besson and F. Faita, "An Event-Related Potential (ERP) Study of Musical Expectancy: Comparison of Musicians with Non-Musicians," *Journal of Experimental Psychology: Human Perception and Performance* **21** (1995) pp. 1278–1296.

18. P. Janata and H. Petsche, "Spectral Analysis of the EEG as a Tool for Evaluating Expectancy Violations of Musical Contexts," *Musical Perception* **10**, No. 3, 281–304 (1993).

19. S. Koelsch, E. Schroger and T.C. Gunter, "Music Matters: Preattentive Musicality of the Human Brain," *Psychophysiology* **39** (2002) pp. 38–48.

20. R. Näätänen, "The Role of Attention in Auditory Information Processing as Revealed by Event-Related Potentials and Other Brain Measures of Cognitive Function," *Behavioral and Brain Sciences* **13** (1990) pp. 201–288.

21. M. Tervaniemi, "Pre-Attentive Processing of Musical Information in the Human Brain," *Journal of New Music Research* **28**, No. 3, 237–245 (1999).

22. B. Hjorth, "EEG Analysis Based on Time Series Properties," *Electroencephalography and Clinical Neurophysiology* **29** (1970) pp. 306–310.

23. C. Anderson and Z. Sijercic, "Classification of EEG Signals from Four Subjects during Five Mental Tasks," in *Solving Engineering Problems with Neural Networks: Proceedings of the Conference on Engineering Applications in Neural Networks (EANN'96)* (Turku, Finland: Systems Engineering Association**,** 1996) pp. 507–514.

24. N. Birbaumer et al., "A Spelling Device for the Paralysed," *Nature* **398** (1999) pp. 297–298.

25. B.O. Peters, G. Pfurtscheller and H. Flyvberg, "Prompt Recognition of Brain States by Their EEG Signals," *Theory in Biosciences* **116** (1997) pp. 290–301.

26. W.D. Penny et al., "EEG-Based Communication: A Pattern Recognition Approach," *IEEE Transactions on Rehabilitation Engineering* **20**, No. 5, 214–216 (1999).

27. H. Petsche and S.C. Etlinger, *EEG and Thinking* (Vienna: Austrian Academy of Sciences, 1998).

28. g.tec—Guger Technologies <http://www.gtec.at/>. Accessed 18 June 2004.

29. The MathWorks <http://www.mathworks.com/>. Accessed 18 June 2004.

30. A. Brouse, "The Interharmonium: An Investigation into Networked Musical Applications and Brainwaves," M.A. dissertation (McGill University, 2001).

31. G. Kramer, ed., *Auditory Display: Sonification, Audification, and Auditory Interfaces* (Reading, MA: Addison-Wesley, 1994).

32. Grass-Telefactor <http://www.grass-telefactor.com/>. Accessed 7 July 2004.

33. See <http://www.motu.com/>. Accessed 7 July 2004.

34. See <http://www.cycling74.com/products/maxmsp.html>. Accessed 6 July 2004.

35. Open Sound Control <http://www.cnmat.berkeley.edu/OpenSoundControl/>. Accessed 7 July 2004.

36. I. Peretz and R.J. Zatorre, *The Cognitive Neuroscience of Music* (Oxford, U.K.: Oxford Univ. Press, 2003).

37. E.R. Miranda, S. Roberts and M. Stokes, "On Generating EEG for Controlling Musical Systems," *Biomedizinische Technik* **49**, No. 1, 75–76 (2004).

38. It is worth mentioning that there are a few commercially available EEG systems that can be used by artists and musicians; for example, the IBVA system and WaveRider. Although these systems have some limitations, they are a good starting point for those wanting to experiment with the concepts presented in this paper. Please see IBVA Technology <http://www.ibva.com/> (accessed 17 June 2004) and MindPeak <http://www.mindpeak.com/> (accessed 14 February 2005).

Manuscript received 1 October 2004.

Eduardo Reck Miranda is the head of computer music research at the University of Plymouth, U.K. He has authored a number of papers and books in the field of computer music. He has made contributions in the fields of speech synthesis, evolutionary music and cognitive neural modeling. His latest album CD, Mother Tongue, *was released by Sargasso, London.*

Andrew Brouse is a composer and researcher. He has lectured on music technology at McGill University and computation arts at Concordia University in Montreal, Canada. Currently he is studying for a Ph.D. in the field of Brain-Computer Music Interface at the University of Plymouth, U.K.