On Harnessing the Electroencephalogram for the Musical Braincap

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> Before you can be fitted with your Braincap, you have to be completely bald. . . . A faint drumming sound accelerated until it became the lowest of audible Cs, then raced up the musical scale until it disappeared beyond the range of the human hearing. . . . He presumed that his neuromuscular control was being tested. . . . (Clarke 1997)

The braincap, as described in *3001: The Final Odyssey,* the concluding edition of Arthur C. Clarke's science fiction classic, is the ultimate human-computer interface: it connects the brain to a system that is able to read thoughts and upload new information. The wearer can in minutes acquire new skills that would otherwise take years to master.

Currently, however, a system that uploads information into the brain cannot exist outside the realm of science fiction, although machines that can read signals from the brain are becoming present-day reality. Furthermore, we should soon be able to control all sorts of devices by our thoughts alone. In 1998, a paper presented at the 9th European Congress of Clinical Neurophysiology already reported impressive advances in research on an electroencephalogram-based system to control a prosthetic hand (Guger and Pfurtscheller 1998). More recently, scientists at Brown University reported the development of a brain-computer interface for a system whereby a monkey controlled a cursor on a computer screen (Turner 2002). At first, the monkey used a joystick to move the cursor. After a while, the joystick was disconnected, and the monkey, who had not realized this, continued moving the cursor by means of tiny electrical signals emanating from an electrode implanted on the monkey's motor cortex (the main brain area for motor control).

We are interested in developing thought-controlled musical devices, and to this end we are currently working on the design of a musical braincap. We are developing technology to interface the brain with music systems and compositional techniques suitable for thought control.

This article focuses on extracting and harnessing tiny electrical brain signals from electroencephalograms (EEGs) that can be captured with electrodes on the scalp. We present three experiments whose results provide the basis for building systems to automatically detect information in the electroencephalogram associated with musical mental activities. Then, we describe how these results are currently being embedded in the design of the musical braincap. Before we present the experiments, we briefly introduce the growing field of Brain-Computer Interfaces (BCI), followed by an introduction to the EEG and the signal processing techniques we employed to harness it.

Before we continue, it is necessary to clarify the meaning of the expression "thought control." In

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this context, thought control should not evoke the idea of a person imagining a specific piece of music that is then magically generated exactly as imagined. This is beyond the capabilities of current science and technology. By thought control, we mean simply using brain signals associated with specific mental activities to interact with musical devices. The sophistication of this interaction will depend upon the nature of the mental activities that one is able to identify in the EEG, the efficiency of the EEG signal-processing techniques employed, and above all, the design of the system in question. We are by no means proposing the naïve scenario of a "high-tech Mozart" who would simply imagine music that the technology then creates.

Brain-Computer Interfaces and Music

Generally speaking, a brain-computer interface (BCI) is a system that allows one to interact with a certain device by means of signals emanating directly from the brain. There are basically two ways of tapping brain signals: invasively and non-invasively. Whereas invasive methods require the placement of sensors connected to the brain inside the skull, non-invasive methods use sensors that can read brain signals from the outside the skull. Invasive technology is becoming increasingly sophisticated, but brain prosthetics is not a viable option for this research. The most viable non-invasive option for tapping the brain for BCI currently is the EEG. It is a well-known phenomenon that brain activity produces a range of electrical signals in the cerebral cortex, generating electrical fields that can be captured using electrodes placed on the scalp. These signals are generally referred to as the EEG. There is a growing number of people developing EEG-based BCI, as could be witnessed at the first international meeting *Brain-Computer Interface Technology: Theory and Practice,* held at the New York State Department of Health, in June 1999. (Unfortunately, no proceedings were published.)

It is possible to identify three categories of BCI systems: user-oriented, computer-oriented, and mutually-oriented.

User-Oriented Systems

In user-oriented BCI systems, the computer adapts to the user. Metaphorically speaking, these systems attempt to "read" the mind of the user to control a device. For example, Anderson and Sijercic (1996) reported on the development of a BCI controller that learns how to associate specific EEG patterns from a subject to commands for navigating a wheelchair. The prosthetic hand and the monkey experiment mentioned earlier also fit into this category.

Computer-Oriented Systems

With computer-oriented BCI systems, the user adapts to the computer. These systems rely on the capacity of the users to learn to control specific aspects of their EEG, 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 the computer screen (Birbaumer et al. 1999).

Mutually-Oriented Systems

Finally, mutually-oriented BCI systems combine the functionalities of both categories, where 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 (Peters, Pfurtscheller, and Flyvberg 1997; Penny et al. 1999). Co-evolving systems of humans and computers belong in this category.

BCI Music Controllers

To date, most efforts of BCI research have been aimed at developing ways to help severely impaired people communicate via computer systems and/or control mechanical tools, such as a wheelchair or a prosthetic organ. However, very little has been done to address the use of BCI technology for musical applications; such applications could undoubtedly improve the life quality of physically impaired people in many forms, ranging from entertainment to therapy.

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 waveband to specific musical actions. These are essentially computer-oriented systems, as they require the user to learn to control their EEG in a certain way. This is very difficult to achieve without appropriate training. An effective method for learning to achieve specific mental states is based upon the notion of *biofeedback*. Biofeedback is a therapeutic technique whereby patients are trained to improve their condition by altering body functions that are involuntary, such as blood pressure, body temperature, and EEG (Robbins 2000).

The idea of thought-controlled music can be traced back to the 1960s, when Alvin Lucier composed *Music for Solo Performer*, a piece for percussion instruments played by the vibrations produced from the performer's EEG (Lucier 1976). Lucier placed electrodes on his scalp, amplified the signals, and relayed them onto loudspeakers that were coupled to cymbals, gongs, and drums. The sounds emitted by the loudspeakers set the surfaces and membranes of the percussion instruments into vibration.

It was David Rosenboom, however, who in the early 1970s began systematic research into the potential of EEGs to generate art works, including music (Rosenboom 1990a). Drawing on concepts from electroencephalography (Niedermeyer and Lopes da Silva 1987) and cybernetics (Wiener 1948), he developed EEG-based musical interfaces associated with a number of compositional and performance environments that used the latest EEG technology at the time. In particular, Mr. Rosenboom explored the hypothesis that it should be possible to detect the occurrence of certain aspects of our musical experience in the EEG signal. For example, he introduced a generative music system whose parameters were driven by EEG components believed to be associated with shifts of the performer's selective attention (Rosenboom 1990b).

We have tried to replicate the system described in Mr. Rosenboom's 1990 article, but we found it extremely difficult to establish whether our system was really detecting shift of attention in the EEG. In the case of Mr. Rosenboom's work, however, this was not necessarily a problem. On the contrary, his objective was to allow the performing subject's EEG to influence the evolving musical forms, regardless of whether they were always aware of the events. All the same, his work is undoubtedly a landmark in the field of BCI for musical applications, as it indicates that the notion of thought-controlled musical systems is indeed possible. The core idea is to control or influence generative musical processes using EEG information about the musical experience of a performer during the unfolding of the piece. The sophistication of such a system is largely dependent upon its ability to harness the EEG signal and to devise suitable generative music strategies. We believe that we can push Mr. Rosenboom's initial ideas much further by taking the progress made in the last decade in the fields of artificial intelligence, EEG analysis technology, and digital signal processing.

Several commercial systems can play music from EEG data. These normally consist of a headband furnished with two or three electrodes intended to read the EEG from the forehead of the subject. The signal is sent to a computer running software that allows associations of notes or musical events to incoming EEG data. For example, if the EEG's predominant frequency components are lower than 10 Hz, then the system might play sound 1, otherwise play sound 2, and so on. As an excellent example of such a system, we cite the IBVA system designed by IBVA Technologies (refer to Miranda 2001 for a succinct description).

On the whole, these systems do a good job of capturing the EEG from the forehead, but they are rather limited when it comes to using the EEG in meaningful ways. The problem is that the raw EEG data is a stream of unsystematic, "random-like" numbers of little musical interest. Sophisticated analysis tools are needed to decipher the complexity of the EEG before any attempt is made to associate it with musical parameters, and this is a very difficult problem. Apart from breaking the EEG signal into different frequency bands, such systems lack the ability to detect useful information in the EEG. Consequently, they are unable to offer generative music strategies that would take advantage of such information. Our objective is to go beyond

Table 1. Bands of EEG activity and associated mental states for a healthy young adult

EEG Rhythm	*Frequency Band*	*Mental Association*
Delta	$\delta \leq 4$Hz	Sleep
Theta	4 Hz $< \theta \leq$ 8 Hz	Drowsiness, trance, deep relaxation, deep meditation, hypnosis
Alpha	8 Hz $< \alpha \leq$ 13 Hz	Relaxed wakefulness, (normally generated by closing the eyes)
Low Beta	13 Hz $< \beta(-) \leq$ 20 Hz	Awake, alertness, moderate mental activity
Medium Beta	20 Hz $< \beta(m) \leq$ 30 Hz	High alertness, intense mental activity
Gamma (also referred to as High Beta)	$\gamma >$ 30 Hz	Hyper-awareness, stress, anxiety

simplistic EEG waveband associations and computer-oriented BCI systems in a variety of important ways.

The Electroencephalogram (EEG)

As previously mentioned, neural activity generates electric fields that can be recorded with electrodes placed on the scalp (Misulis 1997). The EEG is the visual plot of this signal, but today people normally use the term "EEG" to refer to the electric fields themselves. These electric fields are extremely faint, with amplitudes on the order of only a few microvolts. To be displayed and/or processed, these signals must be amplified. 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. Normally, this reference is an electrode placed in a location that is assumed to lack brain activity, such as the earlobe or the nose. It is also common practice to calculate the EEG of an electrode by averaging the signal from all electrodes and then subtracting it from the signal of each electrode. As far as BCI research is concerned, most of the important EEG activity lies below 40 Hz.

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. Although experts can often diagnose brain malfunctioning from raw EEG plots, this signal must be further scrutinized with signal processing and analysis techniques in order to be of any use for our research.

There are three fundamental approaches to EEG analysis: *power spectrum analysis, event-related potential analysis,* and *correlation analysis.* A brief introduction to EEG power spectrum analysis is given below owing to its relevance to BCI research in general. Event-related potential analysis and correlation analysis lie beyond the scope of this article. More information on how these have been employed in neuroscience of music research can be found in Besson and Faita (1995); Janata and Petsche (1993); Koelsch, Schroger, and Gunter (2002); Näätänen (1990); and Tervaniemi (1999).

Power Spectrum Analysis

Spectrum analysis is primarily based on Fourier techniques, such as the Discrete Fourier Transform (DFT), familiar to many electronic musicians (e.g., Miranda 1998). In short, DFT analysis breaks the EEG signal into different frequency bands and reveals the distribution of power among them. 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 is associated with a state of drowsiness, whereas a spectrum with salient high-frequency components is associated with a state of alertness.

There are six recognized bands of EEG activity, also referred to as *EEG rhythms,* each of which is associated with specific mental states. Experts disagree about the exact frequency boundaries of these bands and the mental states that are associated with each. Table 1 gives what the authors perceive to be consensual values and plausible associations.

Figure 1. (a) EEG spectrum of a subject watching television, and (b) EEG while the same subject is relaxed listening to ambient music with closed eyes. These EEG data were acquired using the IBVA system, with three electrodes placed on the forehead of the subject.

(a)

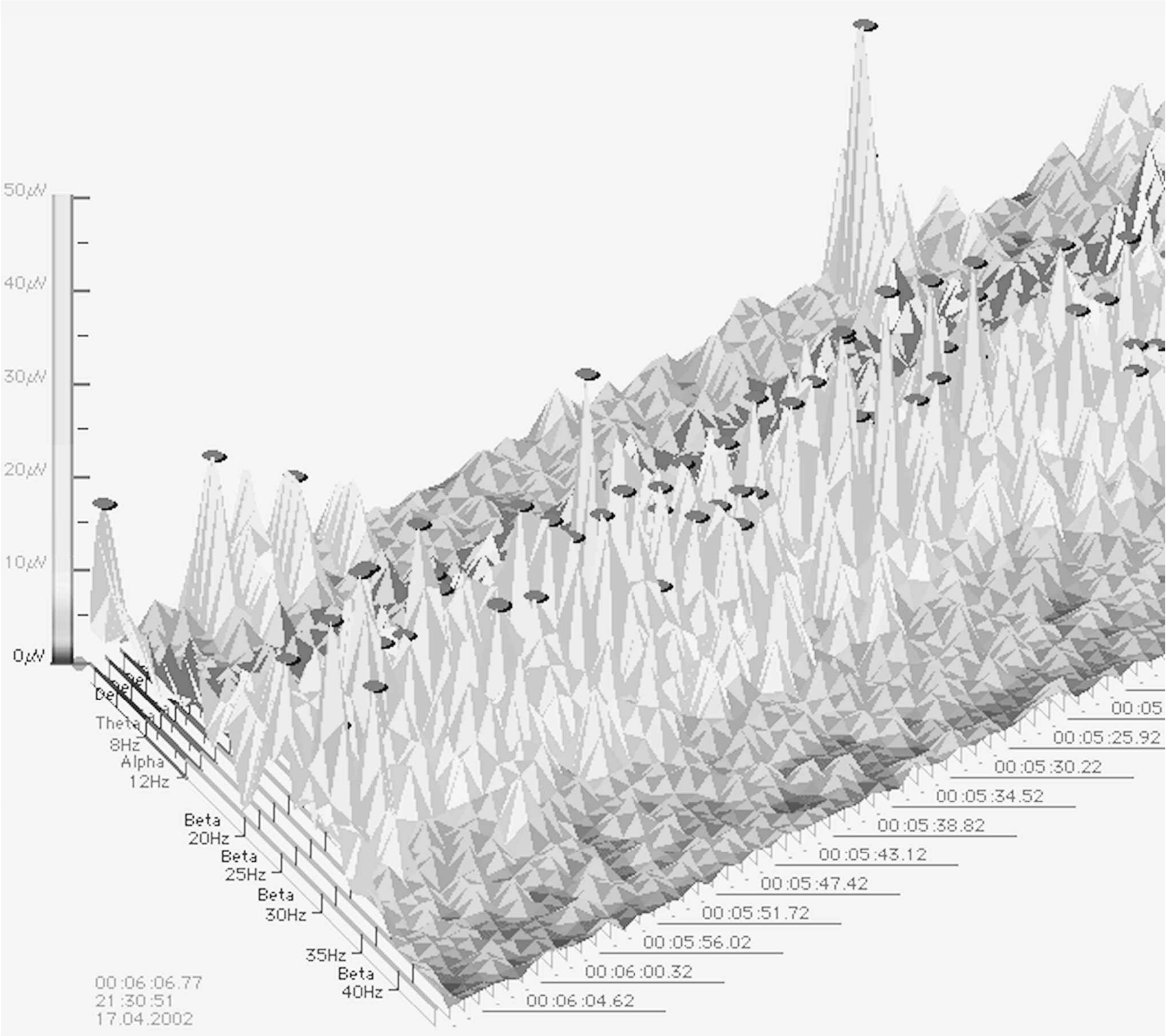

Figure 1 shows two EEG spectral plots taken while a subject was watching television (Figure 1a) and while the same subject was relaxed, listening to ambient music with closed eyes (Figure 1b). Notice the broad band of beta activity in Figure 1a, which indicates that the subject is focusing attention and engaged in intense mental activity. The plot in Figure 1b shows moderate delta and theta activity, and a very narrow band of beta activity, which indicates a deep relaxation with a moderate degree of mental activity.

EEG rhythms clearly are a good source of information about mental activity, but they reveal only the "tip of the iceberg." We must find new meth-