The Science-Music Borderlands

Reckoning with the Past and Imagining the Future

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10 Toward Neurotechnology for Musical Creativity

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> [*Editors' note*: Moving toward a truly coevolutionary view of music and the mind entails going beyond the standard model of a unidirectional arrow from brain to mind in music perception and production. While technologies that would realize music directly from the brain in transparent, unidirectional ways have appeared in science fiction, the practice of developing and working with such tools supports a co-constitutive view. Brain-computer music interfaces are informed by a rich tradition in experimental music (e.g., see Alvin Lucier's 1965 *Piece for Solo Performer*; Leslie's chapter 13 in this volume). Recent developments continue to open up novel possibilities for musical creativity, testing theories in the music sciences such as embodiment and extended mind theory (cf. Witek's chapter 7 in this volume) while offering practical applications for music production in those whose physical limitations may hinder more conventional forms of music making. As a model for new directions in the science-music borderlands, we asked Eduardo Miranda, an expert in brain-computer music interfacing, to describe some of his work in this area.]

Introduction

Imagine if you could play a musical instrument with signals detected directly from your brain. Would it be possible to generate music that represents brain activity? What would the music of our brains sound like? These are some of the questions addressed by research into music neurotechnology,[1] a relatively new field of investigation that is emerging at the crossroads of neurobiology, engineering sciences, and music. Systems that interact directly with the human nervous system (Rosenboom, 2003), sonification methods to diagnose brain disorders (Vialatte et al., 2012), and biocomputing devices (Braund & Miranda, 2015) are emerging as plausible technologies for musical creativity. Such things were unthinkable until very recently.

Many recent advances in the neurosciences, especially in computational neuroscience, have led to a deeper understanding of the behavior of individual and large groups of biological neurons. This enables artists and musicians to apply biologically informed functional paradigms to problems of creativity, design, and control, such as building mind-controlled musical instruments.

An increasingly better understanding of the brain, combined with the emergence of sophisticated brain scanning technology, is enabling the development of brain-computer interfaces (BCIs). BCIs have tremendous potential to facilitate active music making by people with severe physical impairments, such as paralysis after a stroke or an accident damaging the spinal cord. In addition, BCIs present new ways to harness creative practices.

This chapter discusses two projects being conducted at the University of Plymouth's Interdisciplinary Centre for Computer Music Research in the UK. One concerns the development of methods to compose music inspired and informed by neurobiology. More specifically, we created *Symphony of Minds Listening*, an experimental symphonic piece in three movements based on functional magnetic resonance imaging (fMRI) brain scans. Then we introduced our work into developing brain-computer music interfacing (BCMI) technology and created a composition and performance using that technology.

Listening to Minds Listening

Symphony of Minds Listening is based on the fMRI brain scans from three persons—a ballerina, a philosopher, and a composer[2]—while they listened to the second movement of Ludwig van Beethoven's Seventh Symphony.

In a nutshell, we deconstructed the Beethoven movement to its essential elements and stored them with information representing their structural features. Then we reassembled (or remixed) these elements into a new composition, but with a twist: the fMRI information influenced the process of remixing the music. However, *Symphony of Minds Listening* was scored for the same instrumentation as Beethoven's Seventh Symphony.

The fMRI brain scanning method measures brain activity by detecting changes in blood flow. The brain images were collected using equipment and parameters that are typical in the field of cognitive neuroscience. The measurements can be presented graphically by color-coding the strength of activation across the brain. Each scanning session generated sets of fMRI data, each of which was associated with one measure of the second movement of Beethoven's Seventh Symphony.

The score of Beethoven's movement was deconstructed with custom-made artificial intelligence software that extracted statistical information about the structure of the music (Gimenes & Miranda, 2011). We used this information to reconstruct the Beethoven movement, but the reconstruction process was influenced by the fMRI data; effectively, the fMRI data altered the original music.[3] Not surprisingly, the fMRI scans differed among the three listeners. Therefore, activity from three different brains yielded three different movements for the resulting composition. Each of the movements displayed varying degrees of resemblance to the original symphony.

The Compositional Process

The compositional process involved manual and computer-automated procedures. Historically, there have been two approaches to using computer-generated materials in composition: *purist* and *utilitarian*. The purist approach to computer-generated music tends to be more concerned with the correct application of the rules programmed into the system than with the musical results per se. In this case, the output of the computer is considered the final composition. The composer would not normally modify the music at this point, as this would meddle with the integrity of the model or the system. At the other end of the spectrum is the utilitarian approach, adopted by those composers who consider output from the computer raw material for further work. These composers would normally tweak the results to fit their aesthetic preferences, to such an extent that the system's output might not be identifiable in the final composition. Obviously, the line dividing these two approaches is blurred, as practices combining aspects of both are common. Although *Symphony of Minds Listening* was composed with a balanced approach, it tends toward the utilitarian. This author advocates the use of computers as assistants to the creative process, rather than as autonomous composing machines. (For a discussion of how science and technology can inform and inspire the act of musical composition, see Miranda, 2013, 2014b; chapters 13 and 14 in this volume.)

The composition of the symphony evolved in tandem with the development of a piece of generative music software, referred to as MusEng. MusEng was programmed with artificial intelligence to learn musical information from given pieces and use this information to generate new music. The system has three distinct phases of operation: *learning*, *generative*, and *transformative*.

The learning phase takes a musical score and analyzes it to determine a number of musical features. A data set comprising these features and rules representing the likelihood of given features appearing in the data are then stored in memory. During the generative phase, these data inform the generation of new sequences, which ideally should resemble the sequences used to train the system in the first phase. Finally, at the transformative phase, the outcome from the generative phase is modified according to a number of transformation algorithms. It is during this final phase that the fMRI information is used to influence the resulting music. Note that we are not interested in a system of rules that reproduces an exact copy of the original music. Rather, we are interested in producing new music that resembles the original. Hence the transformative phase was added to further modify the results from the generative phase. The role of fMRI information is to control the extent of the transformation. Essentially, stronger activity in a given statistical component of the fMRI data results in greater transformation of the musical outcome.

For the composition of *Symphony of Minds Listening*, the first step was to deconstruct the score of Beethoven's composition into a set of basic materials. These materials were then given to MusEng for processing.

First, Beethoven's piece was divided into 13 sections, ranging from 5 to 26 measures in length. The 13 sections informed the overarching structure of each of the three movements of the new symphony. This provided a template for the new piece, which preserved the overall form of the original Beethoven movement.

Note that MusEng did not learn the whole Beethoven piece at once. Rather, it was trained on a section-by-section basis. The musical sequences for the respective new sections of the new movements were generated independently from each other. For instance, section 1 of the movement *Ballerina* has 26 measures and was composed based on materials from the first 26 measures of Beethoven's music. Section 2 has 24 measures and was composed based on materials from the next 24 measures (27–50) of Beethoven's music, and so on.

A block diagram portraying the compositional process is shown in figure 10.1. The blocks with thicker borders represent procedures that can be influenced and/or controlled by fMRI results. After the music's segmentation into 13 sections, the flow of action bifurcates into two possibilities: manual handling of the segments (left-hand side of figure 10.1) or computerized handling with MusEng (right-hand side of figure 10.1). A discussion of manual handling is beyond the scope of this chapter.

Finally, once a new segment has been generated, it is orchestrated and appended to the respective score of the new movement. Occasionally, the fMRI results also influenced instrumentation and orchestration. For instance, in *Philosopher*, the second movement, different independent components (ICs) were associated with groups of instruments in the orchestra (IC 25 = violins and violas, IC 15 = trumpets and horns, and so on); these associations changed from section to section. So, if the flute is to play in measure *x* of *Philosopher*, the IC value of the respective component in measure *x* of Beethoven's music would define how the flute player should produce the notes.

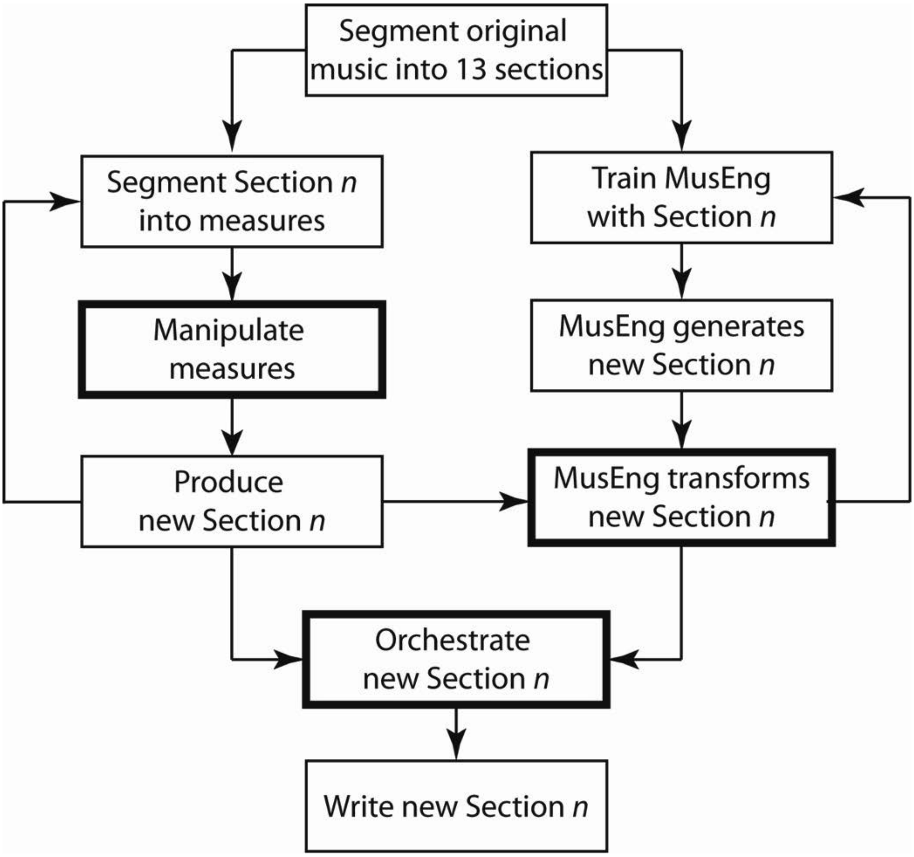

Figure 10.1
Block diagram of the overall compositional process.

We defined various tables mapping IC activity to instrumental playing techniques and other musical parameters, such as onto a continuum of musical dynamics. A detailed technical explanation of the learning and generative phases of the MusEng system is beyond the scope of this chapter (the reader is invited to consult Miranda, 2014a, for more information).

Brain-Computer Music Interfacing

BCI technology allows a person to control devices by commands expressed as brain signals, which are detected through brain monitoring technology (Dornhege et al., 2007).

We are interested in developing BCI technology for music (BCMI).[4] Our research is aimed at music therapy and people with special needs, particularly those with severe physical disabilities but with relatively preserved cognitive functions. Severe brain injury, spinal cord injury, and locked-in syndrome result in weak, minimal, or no active movement, which curbs the ability to play a musical instrument. People with these conditions are currently either excluded from music recreation and therapy or able to engage only in a less active manner through listening or receptive methods (Miranda et al., 2011).

Currently, the most viable and practical method of detecting brain signals for BCMI is the electroencephalogram (EEG), which records electrical signals through electrodes placed on the scalp. The EEG expresses the overall electrical activity of millions of neurons. It is a difficult signal to detect because it is extremely faint. Moreover, the signal is filtered by the membranes that separate the cortex from the skull, the skull itself, and the scalp. To be used in BCI, this signal needs to be amplified significantly and harnessed through signal processing techniques (Miranda, 2010; Miranda et al., 2014).

In general, power spectrum analysis is the most commonly used method of analyzing the EEG signal. In simple terms, power spectrum analysis breaks the EEG signal into different frequency bands and reveals the distribution of power between them. 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. Recognized bands of EEG activity below 40 Hz, also referred to as EEG rhythms, are associated with specific states of mind. For instance, the frequencies falling between 8 and 13 Hz, referred to as alpha rhythms, are usually associated with a state of relaxed wakefulness, such as during meditation. The exact boundaries of these bands are not clearly defined, and the meanings of these associations can be contentious. In practice, however, the exact meaning of EEG rhythms is not crucial for a BCI system. What is crucial is the ability to establish whether users can voluntarily produce power within distinct frequency bands. For instance, we have used alpha rhythms in an early proof-of-concept BCMI system that enabled a person to switch between two types of generative algorithms to produce music on a musical instrument digital interface (MIDI)–controlled Disklavier piano in the style of Robert Schumann (when alpha rhythms were detected in the EEG) and Ludwig van Beethoven (when alpha rhythms were not detected) (Miranda, 2006).

Broadly speaking, there are two approaches to manipulating EEGs for BCI: *conscious effort* and *operant conditioning*. Conscious effort induces changes in the EEG when the subject engages in specific cognitive tasks designed to produce specific EEG activity (Miranda et al., 2004; Curran & Stokes, 2003). The cognitive task used most often is motor imagery because it is possible to detect changes in the EEG of a subject who is imagining moving a limb, such as a hand (Dornhege et al., 2007). Operant conditioning involves the presentation of a task in conjunction with some form of feedback, which allows the user to develop a somewhat unconscious control of the EEG (Kaplan et al., 2005).

A steady-state visual evoked potential (SSVEP) is a robust paradigm for BCI, as long as the user is not severely visually impaired. Typically, visual stimuli representing tasks to be performed are presented to a user on a computer monitor; such tasks might include spelling words from an alphabet or selecting in which direction a wheelchair moves. Each target is encoded by a flashing visual pattern reversing at a unique frequency. To select a target, the user simply directs his or her gaze at the flashing pattern corresponding to the action to be performed. As the user's spotlight of attention falls on a particular target, the frequency of the unique pattern reversal rate can be accurately detected in the EEG through spectral analysis. It is possible to classify not only a user's choice of target but also the extent to which the user is attending to the target. This allows SSVEP-based BCI systems in which each target is not a simple binary switch but represents an array of options, depending on the user's level of attention. Effectively, each target of such a system can be implemented as a switch with a potentiometer.

An Initial SSVEP BCMI System

In 2011 we completed the implementation of our first SSVEP-based BCMI system, which we tested on a patient with locked-in syndrome at the Royal Hospital for Neurodisability in London. The system comprised four targets, shown on a computer screen in front of the patient. Each target image represented a different musical instrument and a sequence of notes (figure 10.2). Each image flashed, reversing its color (in this case, red) at different frequencies: 7 Hz, 9 Hz, 11 Hz, and 15 Hz, respectively. For instance if the person gazed at the image flashing at 15 Hz, the system activated the xylophone and produced a melody using a sequence of six notes associated with this target; these notes were set beforehand, and the number of notes could be other than six. The more the person attended to this icon, the more prominent the magnitude of the brain's SSVEP response to this stimulus, and vice versa. This produced a varying control signal, which was used to make the melody. Also, it provided visual feedback to the user; the size of the icon increased or decreased as a function of this control signal.

The melody was generated as follows: The sequence of notes was stored in an array whose index varied, in this case, from one to six. The amplitude of the SSVEP signal was normalized so that it could be used as an index sliding up and down through the array. As the signal varied, the corresponding index triggered the respective musical notes stored in the array.

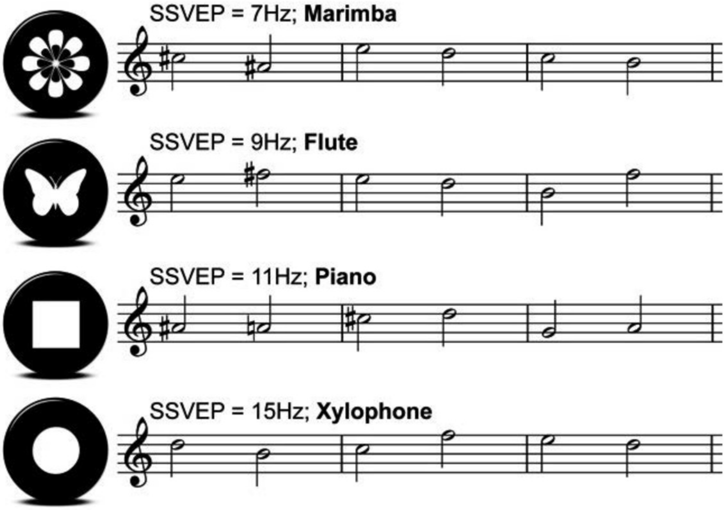

Figure 10.2
Each target image is associated with a musical instrument and a sequence of notes.

The system required just three electrodes on the user's scalp: a pair placed on the region of the visual cortex and a ground electrode placed on the front of the head. Filters were programmed to reduce noise interference and artifacts such as those generated by blinking eyes or moving facial muscles. SSVEP data were then filtered via band-pass filters to measure the band power across the frequencies correlating to the flashing stimuli.

The patient took approximately fifteen minutes to learn how to use the system, and she quickly mastered how to make melodies by increasing and decreasing the level of her SSVEP signal. We collected suggestions and criticisms from the hospital staff and the patient with respect to improvements and future developments (Miranda et al., 2011). An important challenge emerged from this exercise: our system enabled a one-to-one interaction with a musical system, but it was immediately apparent that it would be desirable to design a system that would promote interaction among the participants.

Activating Memory and The Paramusical Ensemble

To address the above-mentioned challenge, we adopted a slightly different research methodology. We started by imagining a musical composition and a performance scenario. Only then did we consider how that would work in practice with our BCMI technology. To tackle the problem of lack of expressivity, we decided to have the user generate a score on the fly for a human musician to sight-read, instead of relaying it to a synthesizer for playback.

To promote group interaction, we determined that the composition had to be generated collectively by a group of participants. However, the generative process had to be simple and clearly understood by the participants. Also, the controlling-brain participants had to clearly feel that they were in control of what was happening with the music. Obviously, these were not trivial tasks. In the end, we established that the act of collectively generating the music in real time could be like playing a musical game, but with no winners or losers. We thought of designing something resembling a game of dominoes—that is, musical dominoes played by sequencing blocks of precomposed musical phrases selected from a pool. Finally, we created the concept of a musical ensemble where severely physically disabled and nondisabled musicians made music together: The Paramusical Ensemble. The result was the composition *Activating Memory*, a piece for eight participants: a string quartet and a BCMI quartet.

A new version of the SSVEP-based system was built. Each member of the BCMI quartet was furnished with a unit of the new SSVEP-based BCMI system. The system enabled them to generate a musical score in real time. Each participant generated a part for the string quartet, which was displayed on a computer screen for the respective string performer to sight-read during the performance (figure 10.3).

Figure 10.3
A rehearsal of The Paramusical Ensemble, with locked-in syndrome patients performing *Activating Memory*.

The new system worked similarly to the one described in the previous section, with the fundamental difference being that the visual targets were associated with short musical phrases. Moreover, instead of flashing images on a computer monitor, we built devices with flashing LEDs and LCD screens to display what the LEDs represented.

The LED devices increased the SSVEP response to the stimuli because we were able to produce more precise flashing rates than those produced using standard computer monitors. Moreover, the LCD screens provided an efficient way to change the set of options available for selection. And it promoted the notion that one was using a custom-made musical device to interact with others, rather interacting via a computer.

Activating Memory was generated on the fly by sequencing four voices of predetermined musical sections simultaneously. For each section, the system provided four choices of musical phrases, or riffs, for each part of the string quartet, which were selected by the BCMI quartet. The selected riffs for each instrument were relayed to the computer monitors facing the string quartet for sight-reading. While the string quartet was playing the riffs for a section, the system provided the BCMI quartet with another set of choices for the next section. Once the current section had been played, the new riffs chosen for each instrument were relayed to the musicians, and so on. To allow enough time for the BCMI quartet to make choices, the musicians repeated the respective riffs a few times. The system followed an internal metronome, which guaranteed synchronization. The Paramusical Ensemble's first public performance of *Activating Memory* took place on July 17, 2015, at the Royal Hospital for Neuro-disability in Putney, London.[5]

Concluding Remarks

This chapter examined how the neurosciences can be harnessed to develop technologies and methodologies for composing music. We introduced two new pieces of music and the respective technomethodologies developed to compose them.

With *Symphony of Minds Listening*, we introduced an approach to musical composition inspired by the notion that the neural patterns and corresponding mental images and events around us are creations of the brain prompted by the information we receive through our senses.

Even though humans have identical mechanisms for processing the basics of sound, music is a construction of the brain. There is increasing evidence that this construction differs from person to person. When we listen to music, sounds are deconstructed as soon as they enter the ear. Different streams of neuronally coded data travel through distinct auditory pathways toward cortical structures, such as the auditory cortex and beyond, where the data are reconstructed and mingled with data from other senses and memories into what is perceived as music (Thaut & Hodges, 2019; Arbib, 2013; Peretz & Zatorre, 2003).

Metaphorically speaking, the compositional approach we developed to compose *Symphony of Minds Listening* did to Beethoven's score what our hearing system does when we listen to music: sounds are deconstructed as they enter the ear and relayed through various pathways toward cortical structures, where the data are reconstructed into what is perceived as music.

The BCMI research behind *Activating Memory* has come a long way since the 1960s. Today, meaning derived from EEGs is better understood and easier to detect. However, it is still difficult to retrieve useful EEG data. Signal interference from external sources, unpredictable EEG information, and other physiological input are widely reported by the BCMI research community.

More generally, this chapter presented approaches to leverage our understanding of the brain to compose music. Every now and then, composers have been inspired by science to compose: works such as Gustav Holst's *The Planets Suite* (1918) and Philip Glass's *Einstein on the Beach* (1976) come to mind. Beyond compositions inspired by science, however, we advocate music *informed* by science. The compositions presented in this chapter prompted the author to become conversant with neuroscience and medical engineering. This created opportunities to gain insight and make scientific contributions. Thanks to increased access to scientific information and discovery (e.g., open access to research journals and freely available online repositories for academic prepublications), musicians and artists in general have an unprecedented opportunity to engage with the scientific community, not only to inform their creations but also to establish partnerships for the development of interdisciplinary projects that can impact both the arts and the sciences.

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Notes

1. The term *music neurotechnology* first appeared in print in 2009 in an editorial in *Computer Music Journal*, *33*(1), 1.

2. The composer is this author.

3. We used a musical instrument digital interface (MIDI) representation of the score to process the music.

4. The phrase *brain-computer music interfacing*, or BCMI, was coined by this author to denote BCI systems for musical applications, and it has been adopted by the research community.

5. A video documentary is available at https://vimeo.com/143363985. A recording of one of the millions of possible renderings of *Activating Memory* is available at https://soundcloud.com/ed_miranda/activating-memory.

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