Minding the (Transatlantic) Gap: An Internet-Enabled Acoustic Brain-Computer Music Interface

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ABSTRACT
The use of non-invasive electroencephalography (EEG) in the experimental arts is not a novel concept. Since 1965, EEG has been used in a large number of, sometimes highly sophisticated, systems for musical and artistic expression. However, since the advent of the synthesizer, most such systems have utilized digital and/or synthesized media in sonifying the EEG signals. There have been relatively few attempts to create interfaces for musical expression that allow one to mechanically manipulate acoustic instruments by modulating one's mental state. Secondly, few such systems afford a distributed performance medium, with data transfer and audience participation occurring over the Internet. The use of acoustic instruments and Internet-enabled communication expands the realm of possibilities for musical expression in Brain-Computer Music Interfaces (BCMI), while also introducing additional challenges. In this paper we report and examine a first demonstration (*Music for Online Performer*) of a novel system for Internet-enabled manipulation of robotic acoustic instruments, with feedback, using a non-invasive EEG-based BCI and low-cost, commercially available robotics hardware.

Keywords
EEG, Brain-Computer Music Interface, Internet, Arduino.

1. INTRODUCTION
Electroencephalography, first applied to humans by Hans Berger in 1924, is the recording of summed electrical activity of large populations of similarly oriented and locally synchronous neurons, located primarily in the human neocortex. Although the earliest effort to sonify EEG was reported in a 1934 paper in *Brain* [1] Alvin Lucier's 1965 *Music for Solo Performer* is widely considered the first EEG-based musical composition. Lucier was strongly motivated by "the image of the immobile if not paralyzed human being who, by merely changing states of visual attention, could communicate with a configuration of electronic equipment" [7]. Interestingly, this was nearly a decade before the earliest published attempts by Jacques Vidal and others to create what we now call a brain-machine/computer interface (BMI/BCI), which is a system that uses signals recorded directly from the brain to manipulate an external actuator [14]. In *Solo Performer* Lucier's amplified alpha (8-12.5 Hz) brainwaves were played through loudspeakers coupled to a battery of percussive instruments, allowing him to generate resonant acoustic events by modulating his alpha rhythm. Lucier's pioneering work was followed by a number of artists and throughout the 1960's and 1970's experimentation with brainwave sonification flourished (see [9] for a review). However, this was followed by over a decade of relative silence.

Within the last decade, due in part to successes in the BCI field, there has been a resurgence of interest in the use of EEG-based BCI technology in musical composition leading Miranda and Brouse to coin the term Brain-Computer Music Interface (BCMI) to refer to systems that use a BCI for musical expression [9,10]. Some BCMI researchers have focused primarily on active control of a musical interface using standard BCI tools; for example, Mick Grierson's adaptation of a P300 speller, which allows a user to construct a sequence of musical notes by attending to various symbols on a display [5]. Others have focused on neurofeedback applications and passive cognitive state detection/sonification [6,15]. Still others have explored collaborative sonification of the mental state of multiple individuals simultaneously. For instance, Steve Mann, James Fung, Ariel Garten and Chris Aimone's *Regen/DECONcert* series had dozens of participants don wearable EEG hardware and alter a synthesized music soundscape via changes in their collective alpha activity [8].

Importantly, most of these and other BCMI systems have incorporated local control of a digital and/or synthesized music interface. There have been comparatively few attempts to create BCMI systems that mechanically control acoustic instruments using EEG. As we shall later discuss, the use of visible, acoustic instrument ensembles, with their somewhat anthropomorphic, unpredictable and thus essentially 'human' method of sound production, introduces new aesthetic opportunities and challenges. Secondly, although a number of artists have explored interactive music creation over the Internet (as reviewed in [10]), comparatively fewer Internet-enabled BCMI installations/performances have been developed. One exception is Andrew Brouse's *InterHarmonium* project [3]. As with any other Internet-enabled interactive media system, including the possibility for distributed communication and interaction in a BCMI may significantly expand the range of possibilities for collaborative musical expression and audience participation.

1.1 Music For Online Performer
On January 16, 2010 we premiered *Music for Online Performer* as part of Adam Jansch and Richard Glover's *In Tones: Organ/Radio/Television/Internet* installation series. The name and other subtle references to Lucier's *Solo Performer* – including the use of acoustic percussive instruments – were

chosen due to our mutual respect for Lucier's pioneering work. Here electrical signals recorded from the brain of a participant (T.M.) in San Diego, USA were used to manipulate, in near real-time, acoustic instruments in front of a live audience at Phipps Hall at the University of Huddersfield, UK. Using freely-available Livestream™ and Skype™ technology, the music was streamed back to the conductor/composer (R.W.) in San Francisco and the "brainist" in San Diego, who used this feedback (along with local visual feedback), combined with compositional instructions delivered by the conductor, to manipulate his brain rhythms and thereby inform the ongoing composition. In addition, a live Internet audience watched audio-video feeds from all three locations and was in constant communication with the conductor via a Livestream chatroom, allowing them to indirectly influence the composition.

The installation was structured around the concept of a quartet: four instruments being manipulated by four fundamental neuronal frequency bands estimated from four neural signals recorded from the brain of the solitary performer. The installation was also comprised of four participating parties, distributed around the world but connected via the Internet: the brainist, the composer/conductor, the physical audience (Phipps Hall), and the virtual (Internet) audience.

2. TECHNICAL DESIGN

The design schematic for *Online Performer* is outlined in Figure 1. The brainist is seated in a room in front of two displays, a visual neurofeedback display and a compositional instructions display. Stereo auditory feedback is provided via speakers.

2.1 Data Acquisition

64-channel EEG (Biosemi, Inc) is recorded from the brainist at a sampling rate of 256 Hz. The data is imported into Matlab® (Mathworks, Inc) in 2-second segments using the open-source ERICA/Datariver environment [4]. Due to a hardware issue involving Arduino memory buffer maintenance, data controlling the musical instruments could not be updated faster than 5 instructions/sec. Thus, we fixed the time interval between data segments to 200 ms, although this could theoretically be decreased by at least a factor of 10 or more.

2.2 EEG Features

Each 2-second data segment is separated into 64 maximally independent time series (independent components or "ICs") by projection through a spatial filter previously learned on training data by Independent Component Analysis [2,11]. Here, the training data was a 30-minute long continuous EEG time series recorded from the brainist performing a series of mental exercises, similar to those used to control the music BCI (relaxation, left hand motor imagery, right hand motor imagery, mental calculation). Four of these components are selected based on prior analysis of the spatial topography of the components across the scalp. In our implementation, we selected four components each with spatial filter weights resembling the projection of a single equivalent-current dipole (e.g., a patch of locally synchronous neurons constituting an EEG "source") located near one of frontal midline cortex (FMC), visual cortex (VC), or left or right sensorimotor cortex (lSMC, rSMC).

The power spectral density for each selected IC is then obtained using the Burg method (with an eighth-order autoregressive model) and a bandpower quantity computed by integration over one of four frequency bands. In our implementation, we estimated bandpower for the FMC, VC, lSMC, and rSMC ICs using the respective bands 4-8 Hz (theta), 8-12.5 Hz (alpha), 10-12.5 Hz (mu), 12.5-30 Hz (beta). This

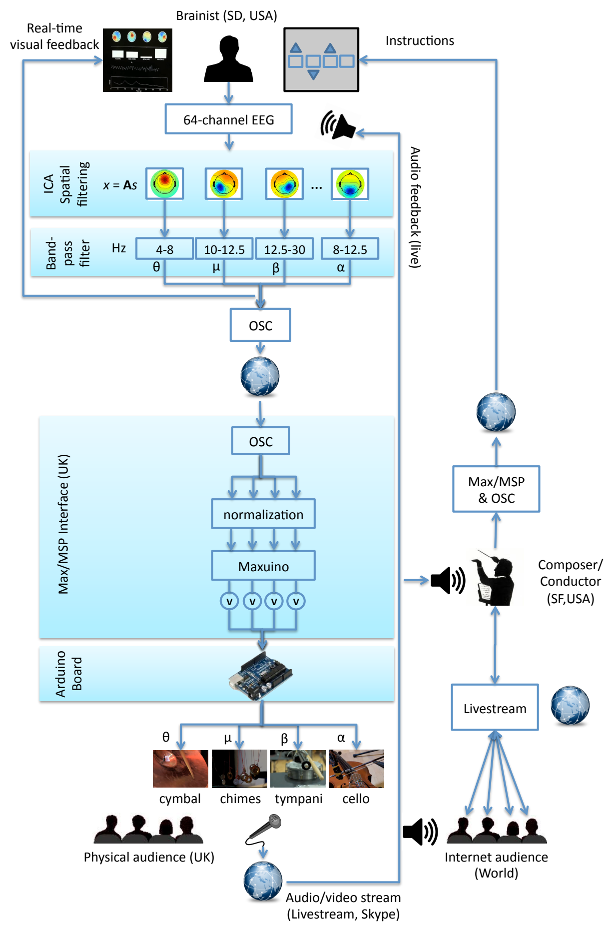

Figure 1. Installation flowchart for *Music for Online Performer*. Globes represent Internet transmission.

choice was informed by a large quantity of published literature relating power modulation in these bands, near the four selected brain areas, to several mental tasks such as motor imagery, mental calculation, and relaxation. Specifically, it is known that motor imagery (imagination of body part movement) leads to a decrease in mu and beta power, termed event-related desynchronization (ERD), in the region of sensorimotor cortex corresponding to the body part being imaged with a concomitant increase in power (event-related synchronization (ERS)) in distal regions of sensorimotor cortex. Relaxation is known to result in alpha ERS in visual cortex, while visual imagery or task engagement/focus leads to alpha ERD. Engagement in tasks with high working memory demands, such as mental calculation, is associated with increases in frontal midline theta power [12,13].

The four bandpower estimates are then fed back to the user via a bar graph display. Such real-time neurofeedback is known to be a powerful tool in improving the ability of an individual to modulate his/her neuronal rhythms and is considered an integral component of a closed-loop BCI [14]. The same bandpower estimates are also simultaneously packaged and transmitted to a computer at the performance site (Phipps Hall, University of Huddersfield, United Kingdom) using Open Sound Control (OSC).

2.3 Acoustic Instrument Control

At the performance site, OSC packets are unpacked and imported into Max/MSP, where the bandpower values are rescaled, converted into servomotor angular rotation values,

Figure 2. Instruments used in Music for Online Performer

and transmitted to an Arduino board over an RS232 (serial) interface using the Maxuino patch developed by Chris Coleman[1]. The Arduino board (we used the Arduino Duemilanove with the ATmega168 microcontroller) uses a mixture of analog and digital pulse-width modulation (PWM) sequences to control four servomotors, each of which mechanically manipulates a separate musical instrument thereby acoustically sonifying the respective bandpower. The four instruments chosen, with respective frequency band / brain anatomy mappings were cello (alpha, VC), chimes/bells, (mu, lSMC), woodblock (beta, rSMC), and cymbal (theta, FMC). The instruments were chosen for their percussive quality (with a nod towards Lucier's own choice of percussive instruments in *Solo Performer*) as well as based on our ability to effectively manipulate the instrument using a simple rotational servomotor. The mechanical devices actuating the instruments (shown in Figure 2) were designed as follows.

The cello, using standard A3/D3/G2/C2 tuning, was played via a cello bow attached to a mechanical 'arm' which connected to a rotational servomotor the angle of which was smoothly varied between 45 and –45 degrees by a 4 Hz oscillator. This produced a "tremolo" effect. The specific note evoked by the tremolo was determined via the brainist's alpha power modulation. Alpha power was scaled to the range [0 90] degrees and added as an offset to the servomotor angle. This changed the mean angle the bow made with the cello neck producing a bowed tremolo over a different subset of strings.

The chime array was actuated by a 9V DC fan whose speed varied inversely proportionate to mu power. The chimes (an array of 20 washer discs ranging in size and weight) were distributed from heaviest to lightest (front to rear) such that increases in fan speed (due to mu ERD) would resonate the heavier chimes resulting in an overall higher pitch effect.

The woodblock was actuated by a double ball-headed drumstick attached at its midpoint to a servo with a 180 degree angular range and positioned over the woodblock. Similar to mu, beta power was inversely mapped to rotation speed such that beta ERD (as occurs in motor imagery) would lead to increased percussive tempo.

The cymbal was actuated by a standard drumstick attached to a 360 degree full-rotation servo via a piece of string and positioned over an upturned cymbal. The angular velocity of the servo was varied proportionately to theta power. This produces a continuous "sweeping" or oscillating timbre whose volume can be varied by modulating the rotational velocity of the servo; increasing the rotational velocity causes the drumstick to brush the cymbal at a higher rate, increasing the resonance of the cymbal and thus the perceived volume.

The frequency-instrument mappings were selected so as to map the more controllable frequencies (respectively, alpha, mu, beta) to the more acoustically salient instruments in the ensemble. Additionally, the mappings were intended to loosely reflect the acoustic qualities of the individual neural frequencies. For instance, the rhythmic sweeping sound of the cymbal was evocative of low-frequency "droning" of a 3-7 Hz theta rhythm while the rapid beating and sharp attack of the woodblock was evocative of the high-frequency beta rhythm.

2.4 Audience Participation and Feedback

In our installation, a live audience in Phipps Hall observed the performance first-hand. Simultaneously, live audio and video (from all three geographic locations) was recorded and streamed over the Internet using freely available software (here, Skype and Livestream) to a virtual global audience. Here we had a public Livestream channel/chatroom setup, which audience members could log in to and communicate with each other and the conductor while watching the live performance.

A branch of the audio stream was transmitted to a composer/conductor in another location (here, San Francisco, USA). The conductor had a Max/MSP control interface, which was linked via OSC to the brainist's compositional instructions/notes display, implemented in Matlab. Based on a predetermined, loosely structured, compositional score and the influences of the audience, the conductor could direct the brainist to individually modulate different instruments (e.g., increase the cello pitch by increasing alpha bandpower through relaxation).

A third branch of the audio stream was fed back to the brainist who could use this, along with visual neurofeedback, to help control his neuronal rhythms. This also allowed the brainist to experience the full musical ensemble, making the BCI-instrument interaction less abstract and affording an element of direct improvisational control in the ongoing evolution of the composition.

3. DISCUSSION

Music for Online Performer was a novel venture in several regards. Perhaps the most important novel element was our use of acoustic media, with instruments actuated by low-cost Arduino robotics hardware. This stands in contrast to the majority of BCMIs that have used digital/synthesized audio as their primary media. The use of acoustic instruments introduces an additional element of uncertainty in performances, which we believe is important for compositional expressiveness. Nuances of the performer's modulation of his or her neural state may result in unpredictable behavior of the instruments, due to the nature of their physical construction. How far one attempts to mentally compensate for this unpredictability is a measure of one's willingness to "let go" of a perfect rendition and leave elements to chance.

Secondly, performances and installations combining BCMI technology and synthesized music can be somewhat abstract and acousmatic in nature. Even when the performer is visible, he or she is often immobile and the mechanism of sound production is unclear. This form of musical expression may alienate some audiences, as there is no immediate physicality to the sounds they are hearing. Using acoustic instruments allows the audience to engage with a method of sound production familiar to them and then move on to trying to understand how these instruments are being controlled.

[1] http://www.maxuino.org/

Aside from the novelty of controlling musical instruments 4000 miles away using one's thoughts, *Online Performer* was also in many ways a social experiment. By allowing audience members from around the globe to be brought together in a virtual space where they could communicate with each other throughout the performance, and influence the ongoing composition through their live interactions with the composer, we sought to highlight new kinds of social environments for musical performance. By encouraging audience participation in the physical musical production we effectively extended the virtual space back into the real and tangible, which, as Marshall McLuhan discusses in his 1994 book *Understanding Media: The Extensions of Man,* is the opposite of what usually happens with technology.

4. CONCLUSIONS AND THE FUTURE

In this paper we reported the live demonstration of a novel Internet-enabled acoustic brain-computer music interface system. To our knowledge, this is the first BCMI that has attempted to mechanically control acoustic instruments over the Internet using non-invasive EEG and low-cost, off-the-shelf Arduino robotics hardware, accessible to most artists and do-it-yourself hobbyists. Although we used medical-grade EEG equipment, affordable, high-quality EEG hardware is now becoming ubiquitous with a number of companies offering dry (gel-free) electrode systems (BrainProducts, Emotiv, Quasar, g.Tec, Nouzz, Neurosky, etc)

Although EEG is not a novel element in the experimental arts, it is only recently, with the advent of low-cost wearable EEG hardware, exponentially increasing computing capabilities, and powerful new signal-processing algorithms from the expanding neuroscience and BCI fields, that we are seeing a renewed interest in and expansion of the applications of EEG technology in the arts. As our knowledge of human cognitive neuroscience increases and low-cost EEG technology advances and becomes ubiquitous, we will see a new generation of artists, technologists, and musicians with a passion for artistically representing and expressing the subtle nuances and inner workings of the human mind via the use of brain-machine interfaces. At the same time, there will be a rise in the number of for-profit companies aimed at this generation of DIY bio-artists. Currently, one such company – InteraXon – has gained worldwide recognition for its development of BCI-enabled artistic performance pieces, including lighting up the CN Tower, Ottawa Parliament Buildings, and Niagara Falls at the 2009 Winter Olympics using wearable EEG (Neurosky's MindSet^{TM}) with brainwaves streamed from Vancouver.

As BCI technology develops, we may one day be able to remove the boundary of sensorimotor input/output and directly communicate our intentions, emotions, and desires to machines and human beings in our surrounding environment as well as across the globe. The effect will be extension of the neurobiological networks underlying thought and body schema representation and expression into much larger, externalized networks encompassing multiple other conscious and nonconscious agents.

In producing *Music for Online Performer* we found a beautiful poetry in the ubiquity and interplay of multi-scaled internalized and externalized networks and loops. On some levels of description, micro- and macroscopic neurobiological networks in the brain of the performer were rapidly transmitting information, translating the conductor's instructions into cognitive thought processes which manifested as detected modulations in neural activity influencing his local feedback display and thereby again his neural processes. Simultaneously, on other levels of description, this same neural information was being routed through megascopic globe-spanning networks, creating live acoustic music halfway around the world, influencing the neurobiological networks – and thereby the perceptions, emotions, and intentions – of others worldwide, and ultimately returning, via the directives of the audience and the human conductor, to again influence the source: a solo performer sitting in a room; alone, yet intimately connected to the world at large.

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