A History of Emerging Paradigms in EEG for Music

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ABSTRACT

In recent years, strides made in the development of Brain-Computer Interface (BCI) technology have foreseen a contemporary evolution in the way we create music with Electroencephalography (EEG). The development of new BCI technology has given musicians the freedom to take their work into new domains for music and art making. However, a fundamental challenge for artists using EEG in their work has been expressivity. In this paper, we demonstrate how emerging paradigms in EEG music are dealing with this issue, and discuss the outlook for the field moving forward.

1. INTRODUCTION

The brain has been a focus in art-making since Alvin Lucier first unlocked the potential of Electroencephalography (EEG) in his 1965 piece "Music for Solo Performer" [1]. Lucier used the amplification of his brain waves to resonate the surface of percussion instruments, creating a scene of wonder for the audience. This work opened the field to pioneers like David Rosenboom [2] and Richard Teitelbaum [3], who further contributed to the advancement and expansion of biofeedback in the arts. Rosenboom in particular is noted for founding the scholarly field associated with EEG art [4]. He famously demonstrated EEG music to the world in 1972 with an on air performance with John Lennon, Yoko Ono and Chuck Berry[1].

Starting in the 1990's, artists and scientists began to develop devices better geared towards the nature of the multimodal work that artists were producing. Knapp and Lusted developed the "Biomuse" interface, a platform which acquired signals from the brain, muscles, heart, eyes, and skin [5]. This system was notably used by biosensor pioneer Atau Tanaka [6]. In the 2000's, the term "Brain-Computer Music Interfaces" was introduced to describe Brain-Computer Interfaces that were developed specifically for music [7]. Miranda et al. described a series of such studies in a 2003 Computer Music Journal (CMJ) article [8].

1 http://davidrosenboom.com/media/brain-music-john-and-yoko

A major benefit of EEG - as opposed to some other brain imaging techniques - is its high time-resolution. Over the decades, this has allowed artists to develop real-time applications that use feedback and sonification in performance and installation. Today, with numerous advancements in commercially available BCI technologies such as dry electrodes and wireless systems, EEG music is experiencing a vast resurgence. This technology makes possible the widespread adoption of this paradigm by artists, providing it can overcome some key challenges.

The progression of EEG music over the decades since Lucier and Rosenboom's works has been discontinuous [9]. Tanaka noted that with the introduction of digital signal processing techniques in the 1980s, there was a "fundamental shift" in artistic interest from biofeedback works to biocontrol [10]. The reproducibility and volition offered by instruments such as electromyography (EMG) began to have greater appeal than the traditional biofeedback techniques used in producing EEG music. EEG systems were viewed as relatively passive in comparison. Today, we can define this as an issue of expressivity, and artists who work with EEG are charged with confronting this in their work.

In this paper, we discuss the issue of expressivity in EEG music. We then introduce some modern approaches within the BCI for music paradigm that show how artists are confronting this issue in their work. These include the development of theatrical performances, immersive environments, interactive and generative systems, notation systems and artistic visualizations of EEG signals. We also discuss an outlook for the field moving forward.

2. EXPRESSIVITY IN EEG MUSIC

Table 1. Fishkin's Four-Levels of Embodiment

Type	Description
Distant	The output is remote
Environmental	The input is surrounded by the output
Nearby	The input is tightly coupled with the output
Full	The input itself is the output

In Fishkin's research on Tangible User Interfaces, the definition of embodiment, referring to a level of self-contain, is encapsulated in the question, "How closely tied is the input focus to the output focus?" [11]. Fishkin's research identifies four-levels of embodiment which are shown in Table 1: Distant, Environment, Nearby, and Full.

Tanaka extends this taxonomy to the development of musical instruments, identifying full embodiment as an implicit goal in the development of expressive instruments [12]. Tanaka states that expressivity is the "specific musical affordances of an instrument that allow the musician performing on the instrument to artfully and reliably articulate sound output of varying nature that communicates musical intent, energy, and emotion to the listener" [12].

The issue for EEG music is that artists and audiences have traditionally viewed EEG and the associated techniques (i.e., sonification, visualization, and biofeedback) as passive and relatively uncontrollable, and therefore "distant" within Fishkin's taxonomy [10]. Distance is a challenge for artists because it limits the potential expressiveness of their artistic output. Today's artists have begun to reimagine the expressivity of EEG music towards more full-embodied systems.

3. EEG IN MUSIC

In this section, we discuss some of the current trends and paradigms in EEG music that are confronting the challenge of expressivity: including the development of immersive environments, theatric performances, collaborative interaction pieces, generative compositions, and score-driven performances - much of this work implements methods of sonifying and visualizing EEG signals. We also provide some examples of how artists are applying these approaches in their work. Although we classify different works into different types of approaches based on the predominant form of expressivity, it is true that most works draw upon multiple methods.

3.1 Reimagining traditional techniques

Two fundamental techniques in EEG art are sonification and visualization. Traditionally these methods have been viewed as passive – distant and environmentally embodied – systems. However, today's artists have been revitalizing these methods in new ways that afford expression unique to the EEG medium.

3.1.1 Sonification

Much like the artists of the biofeedback era, scientific researchers became interested in how the sonification of EEG data could be used towards neural benefit. The field of auditory display has become a popular domain for EEG music in which tightly coupled systems have been developed to express phenomena existing in EEG data.

Hermann et al. have used sonification to show correlation between neural processing and high-level cognitive activity [13]. This work identified three types of sonification that gave researchers specific knowledge about neural processes. Spectral mapping sonification allows for monitoring of specific bands of EEG data through the assigning of sonic materials (e.g. pitch). Distance matrix sonification is concerned with neural synchronizations as a function of time, and expresses this information through a time-dependent distance matrix of spectral vectors. Differential sonification allows for the comparison of data recorded of different conditions in order to detect interesting channels and frequency bands. Hermann et al. have also extracted the polyrhythmic dynamics of the delta and theta rhythms in the brain while participants listened to music [14]. Baier and Hermann introduced a method of sonification of multivariate brain data that utilized arrays of excitable non-linear dynamic systems [15]. Also, Baier et al. have utilized sonification to study the irregularities of spiking in sensory and cortical neurons [16], and in the study of rhythms extracted form epileptic seizures [17][18][19]. These methods demonstrate the ability to isolate and articulate specific events in EEG data towards reproducible musical output, defining more full embodied musical instruments.

Additionally, Filatriau and Kessous use a subtractive synthesis technique to sonify the intensities of the alpha, beta, and theta frequency bands [20]. Malsburg and Illing created a 30 speaker setup through which EEG signal is audified in space[2] [21]. Many of the artistic works discussed in following sections use sonification techniques. Sonification research is expected to continue to grow among both artists and those in the scientific community.

3.1.2 Visualization

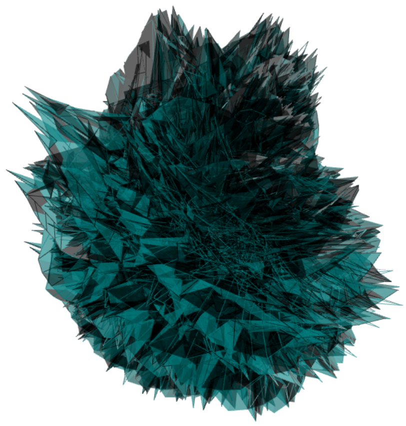

Figure 1. Geometrical Rendered EEG Signal

Today the majority of musical EEG works incorporate multimodal experiences, meaning EEG music is often coupled with visual representations of the same neural activity. This is true of many of the works in this paper. Additionally, several interesting artistic visualizations of EEG signal have been explored in recent years that confront the notion of expressivity.

Tokunaga and Lyons created Enactive Mandala, which sought to encourage meditation of the participants [22]. This approach used a particle system representation that the users could manipulate into elliptical shape through increasing their meditating activity. Such methods make use of black-box algorithms that come built-in to most commercially available BCIs, and use them as control parameters in audio/visual systems. These systems demonstrate a high degree of control and reproducibility. In our own work, we have developed an interesting method in which 3D representations of the EEG signal are rendered for neurofeedback application (see **Figure 1**) [23]. From this we can foresee closer interactions with

2 http://sinuous.de/soundpanel.html

EEG and the structures that make up immersive 3D environments.

3.2 Immersive Spaces

Figure 2. Participatory Life

Immersive audio/visual installation set the audience in a space where they can interact with or be surrounded in representations of neural activity. They have become especially prominent in biofeedback art, where the immersive experience facilitates the neurofeedback process [24].

Thilo Hintenberger demonstrated the power of the immersive environment in his installation, "The Sensorium" [25]. Hintenberger developed a multimodal system that provided both "soundscape" and "lightscape" for the participants. In a pilot study, users reported higher levels of contentment, relaxation, happiness, and inner harmony after interacting with the display. Similarly, the authors' "Participatory life" installation (see **Figure 2**) sets the participant in interaction with an artificial organism that changes in size and kinetic properties in sync with the participant's alpha oscillations [24][26]. Fan et al. developed the "TimeGiver" installation [27]. A multimodal sensor system is used to capture multiple biosignals that are sonified as the ambient tones of the immersive environments (In this case, the environment also becomes collaborative 3.4). Immersive environments are fully embodied in that they essentially become an extension of the user's on body.

3.3 Theatric Performance

Figure 3. Camara Neuronal

Theatrical works showcase the brain in performance, taking advantage of dramatic element of disembodiment in EEG systems by capitalizing on the popular belief that that these systems can detect deeper mental states and thoughts. Lucier's performance in 1965 was as much theatrical as it was the musical:

From the beginning, I was determined to make a live performance work despite the delicate uncertainty of the equipment, difficult to handle even under controlled laboratory conditions. I realized the value of the EEG situation as a theatrical element and knew from experience that live performances were more interesting than recorded ones. I was also touched 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 with what appears to be power from a spiritual realm [28].

In recent years, several artists have taken this approach to EEG in performance. In "Camara Neuronal", Moura et al. used an audio/visual environment to represent the performers' mental and emotional states [29]. **Figure 3** shows how the visual image of the wired performer was essential to the aesthetic composition of the performance of the piece. A similar aesthetic is seen in Claudia Robles Angel's audio/visual performance in which she sought to materialize the performers' mental activity in an immersive space [30]. These types of theatrically expressive performances are becoming ever more popular and some artist are extending this paradigm to audience participation. One such example is the "Accent Project", where audience members use their "focus" levels in order to control their levitation over 30 feet[3].

These theatrical works confront the issue of embodiment by embracing the concept of disembodiment as an aspect of performance in EEG music. Simultaneously, they create a direct extension of the mind to external objects, forging a greater embodiment.

3.4 Collaborative Interaction

Figure 4. Physiopucks on Reactable

Traditionally, EEG music has been linked with interaction with self (i.e. through biofeedback), largely because meditation had been a prominent area of exploration. However research in developing group interactions with this physiological signal has emerged as a new paradigm.

3 http://theascent.co/

Similar to network music performances [31], performers in these works interact with and manipulate shared physiological material such as EEG. While this domain is still in its infancy, a number of interesting works have appeared.

Tiharaglu et al. developed an improvisation platform in which two performers interact with the prerecorded data of a third [32]. Mealla et al. created a tabletop interface (see **Figure 4**) that allowed users to manipulate the physiological signals of others in a collaborative performance [33]. The alpha and theta band were directly mapped to the audible range, while heartbeat was mapped to beats per minute (BPM). A study was run in which two groups could directly manipulate the system, but one group used both explicit gestural and implicit physiological signal control in the interaction, while the placebo group only had explicit control through gesture. The physiological group reported "less difficulty, higher confidence and more symmetric control" in the interaction. This work is also being extended to immersive installations. Mattia Calsalegno developed "Unstable Empathy" in which performers were placed in front of double mirrors and prompted to develop a form of interaction with one another using only their EEG signals that were presented through both audio and video[4].

The fact that the source of the interaction in this domain is physiological data offers an interesting counter to the "unnatural" criticism sometimes ascribed to some network interactions [34].

3.5 Generative Composition

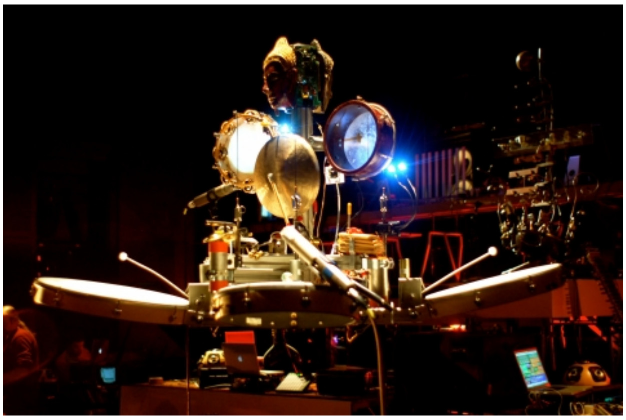

Figure 5. Robot from the Machine Orchestra

Generative systems - commonly referred to as brain-driven instruments - center the brain as a driving source in compositional systems. These systems depend on the extraction of features from neural signals (e.g. frequency bands), and use them to trigger generative rules for musical composition. These approaches have roots in the compositional research of David Rosenboom [4]. This has become one of the more widely explored domains in the development of aesthetic music BCIs, and is in direct contrasts to the passiveness often associated with EEG music, because here the performer is using EEG to drive composition in a meaningful way.

Miranda et al. introduced the *BCMI Piano*, an instrument that incorporates artificial intelligence to generate melodies that are associated with theta, alpha, low beta, and high beta rhythms as well as the *Interharmonium*, a networked synthesis engine controlled by the brains of several users in separate geographic locations [35]. Miranda et al. have also introduced interfaces in which brain activity states are used to control transitions between musical styles by association [36][37].

Wu et al. developed a system that translates mental and emotional information into music material [38], while Arslan et al. developed a synthesis system driven by detection of user intent in EEG and EMG signals [39]. Lu and colleagues have developed several methods of translating EEG signals into scale-free music [40]. In the author's own work, a system was developed based on an algorithmic model of a neuron and neurofeedback. The EEG served as input signals and events caused the neurons to activate. This work was presented using the music robotics at California Institute of the arts[5] [26][41]. Through this system, performer was able to develop an embodied interaction and co-adaptive agency with the robotic instruments around. The audience also relayed theatric appreciation of the performance.

3.6 Score Generation

Figure 6. Multimodal Brain Orchestra

Several new approaches seek to create musical scores through the "P300 speller" [42] and "Steady-state visually evoked potential (SSVEP)" [43] paradigms. The P300 is a positive potential elicited involuntarily about 300ms after an infrequent stimulus occurs. In the P300 Speller, rows and columns of characters are flashed and the P300 is elicited when the set containing the selected character is shown. In the SSVEP paradigm, flashing visual stimuli are presented at differing frequencies evoking a specific synchronized response in the EEG signal for each given target. In both approaches, the artist responds volitionally to a visual signal, creating a measurable neural event. Those neural events are then translated into sound.

The score generation paradigm affords the ability to specifically trigger neural processes according to external stimuli for real-time performance. This is a key component in developing systems with volition and reproducibility, which is essentially the purpose of notated music.

4 http://www.mattiacasalegno.net/unstable-empathy/

5 http://www.youtube.com/watch?v=TQYBTa876KA

These systems have the added ability of not only performance and installation, but also use in assistive applications [44].

Chew and Caspary used the P300 paradigm in a music step sequencer system in which user were able to manipulate musical output by reading through the matrices [45]. Eaton and Miranda applied SSVEP in their generative musical framework "Mind Trio" [46]. Miranda et al. also used SSVEPs in a study that help patients with locked-in systems create music [44]. Le Groux et al. utilized both P300 and SSVEP in their Multimodal Brain Orchestra (shown in **Figure 6**), allowing performers to use these scoring systems for different aspects of the performance [47]. Extending these BCI paradigms has made room for artists to apply these technologies in more traditional music performance settings.

4. DISCUSSION AND OUTLOOK

This paper has presented several approaches currently being explored in EEG music. The majority of the works presented draw on multiple approaches. The expansion of the digital artist and the accessibility of technology led to EEG music becoming a multimodal field in which artists are creating theatrical performances in immersive environments, interactive installation pieces, and collaborative interfaces with this physiological material. The question still remains how sustainable this growth in interest is.

4.1 Expressivity

The current increased interest in EEG is driven by the development of affordable technology and the still mysterious nature of the brain as a tool for external control. Biosensors such as EMG have benefitted from the direct correlation between physical action and musical output, capturing the musical expressions reminiscent of traditional instrumentalists. The question remains whether or not these methods of increasing expressivity will ensure the field's continued growth. As these technologies move into the household, the audience could begin to bore and the widespread interests in this field could begin to fade. On the other hand, the movement of this technology into the household could create a bigger audience for the artist to reach.

4.2 Shared EEG Music

The applications discussed in this paper are making it possible for even those with no musical training to create music. As this technology becomes commonplace, valuable tools can be created to train people to create music based on generative (3.5) and scoring (3.6) type systems. Additionally, we see immersive environments for neurofeedback (3.2) begin to merge with the current boom in Virtual Reality (VR) and Augmented Reality (AR) technology in order provide portable neurofeedback environments.

As BCI technology advances, the areas of application for such technology will grow, and as suggested by some of the works described in this paper, we can expect disembodiment itself to become more of an expression in EEG music rather than a challenge to this emerging paradigm. The nature of the mind and mysteries of how it works reintroduces some fundamental artistic questions to the technological art domain regarding the distinctions between implicit and explicit representation, and between impressionist and expressionist aesthetics.

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