Neurophone: A Brain-Computer Music Interface for Emotional Neurofeedback

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***Abstract*—Music is widely recognized as a powerful tool for emotional regulation and cognitive engagement. Recent advances in wearable systems, signal processing and interactive technologies have enabled the real-time generation and modulation of music based on brain activity, leading to the development of Brain-Computer Music Interfaces (BCMIs). These systems allow users to interact with musical environments through brain electrical signals captured via electroencephalography (EEG). In this work, we present the *Neurophone*, a BCMI that integrates real-time EEG acquisition with dynamic music generation. EEG signals are collected using the Muse S wearable headband and transmitted via Bluetooth to a mobile application. The signals are then forwarded through WiFi using OSC communication protocol to a custom musical feedback system. This system was implemented in Ableton Live, a digital audio workstation (DAW) using Max for Live for programming purposes. The *Neurophone* enables the transduction of five EEG frequency bands into musical parameters such as pitch, velocity, duration, and rhythm. It functions as a real-time musification platform, allowing users to modulate musical expression through their cognitive and emotional states. The instrument emphasizes performance and versatility with a simple plug-and-play integration. The *Neurophone* requires minimal setup and can be readily adapted to different EEG acquisition devices. Preliminary results demonstrate EEG-to-MIDI mapping, showing how distinct frequency bands correlate with specific musical features. This work aims to bridge neuroscience with musical technology, offering an adaptable tool for studying brain responses and interaction with musical environments. The *Neurophone* opens new possibilities for therapeutic applications, creative expression, adaptive music generation, and immersive sound experiences.**

***Index Terms*—Generative music, Brain-Computer Music Interface, Neuroengineering, Signal Processing.**

I. Introduction

Music is a universal cultural phenomenon, widely used to communicate and elicit emotions [1]. Its psychological and physiological effects on the human body have long been of interest in neuroscience [1]–[9]. Music engages mechanisms of the nervous system during rhythmic and tonal processing [7], [10] and can generate intense affective responses [11]. Thus, it provides both a valuable framework for understanding brain function [6] and a potential therapeutic tool for emotional regulation [8], [9].

Neurofeedback has explored music as a means to help individuals modulate mental states by monitoring brain electrical activity and providing real-time feedback [12]. This technique often relies on electroencephalography (EEG), a non-invasive method that records electrical activity through scalp electrodes. EEG signals are decomposed into distinct frequency bands associated with psychological or physiological states: delta (1–4 Hz), theta (4–7 Hz), alpha (8–13 Hz), beta (13–30 Hz), and gamma (>30 Hz) [13]. For example, alpha activity is typically linked to relaxed wakefulness, while beta increases during focused cognitive tasks.

BCIs allow direct control of external devices, including virtual environments and robotic systems, from brain activity [14]. When brain signals are translated into auditory feedback, they enable immersive real-time interaction with sound environments. These systems, known as Brain–Computer Music Interfaces (BCMI) [15], have emerged as promising tools for emotional regulation and could support the treatment of affective disorders such as major depression [16].

In this work, we present the *Neurophone*, a BCMI that modulates musical parameters based on EEG signals. Brain rhythms are acquired in real time from a wearable EEG headband, processed to extract canonical frequency bands, and mapped to parameters such as pitch, velocity, duration, and rhythm. The system enables a personalized closed-loop framework for musical neurofeedback to study brain–music interactions in both physiological and pathological contexts.

Unlike many BCMIs that depend on clinical-grade equipment, the *Neurophone* emphasizes accessibility and portability by using consumer-grade devices (Muse S headband and a low-cost mobile app) together with a widely available music production platform (Ableton Live with Max for Live). This approach makes it affordable for use outside specialized laboratories and represents an initial step toward an Internet of Musical Things (IoMT) application [17]. Neurofeedback data are transmitted from the processing environment to the DAW via OSC and MIDI protocols, positioning the *Neurophone* as a candidate networked instrument.

II. Background

Brain–Computer Music Interfaces (BCMI) integrate music and technology to study how the brain processes and interacts with sound in real time. Auditory paradigms based on EEG include sonification, musification, and BCI control [18], [19]. Sonification refers to rendering EEG data into sound for non-musical or clinical purposes, whereas musification maps EEG features to musical parameters such as pitch or timbre, often yielding expressive but unpredictable results. Full BCI control occurs when users intentionally modulate the output through learned cognitive strategies, forming the basis of neurofeedback [18], [19]. BCMIs have been applied in both therapeutic and artistic contexts.

Music has also been explored as a therapeutic stimulus in EEG-based neurofeedback. In a systematic review of 33 studies (2000–2023), Sayal et al. [20] categorized applications into: (i) music as auditory stimulus to elicit responses, (ii) music generation from EEG features, and (iii) adaptive neurofeedback through music. The review emphasized growing interest in BCMIs for emotional regulation, cognitive enhancement, and mental health, while noting persistent challenges such as the absence of neurophysiological models, methodological heterogeneity, and lack of standardized evaluation. Initiatives like the CRED-nf checklist seek to improve reporting practices, but adoption remains limited [20], [21].

Neurophysiological evidence further supports the role of auditory rhythms in modulating brain activity. Musical stimuli can entrain neural oscillations by synchronizing EEG phase with external rhythms, a phenomenon known as neural entrainment [22]. While not itself a BCMI technique, this provides a mechanistic basis for incorporating music and rhythm into closed-loop neurofeedback systems.

BCMIs have also been used in artistic domains. In *Music for Solo Performer* (1965), Alvin Lucier employed alpha waves (8–13 Hz) to activate percussion instruments, establishing a seminal reference for artistic uses of brain signals [23]. More recently, closed-loop systems for continuous affective interaction have been proposed [24], often relying on models of valence and arousal [25]. Other examples include the *Encephalophone*, which maps alpha and beta power to pitch for hands-free performance [26], the pioneering multimodal *BioMuse* [27], and Brain–Body Digital Musical Instruments using higher-level feature recognition [28]. These works highlight the evolution of BCMIs toward richer models of brain–music interaction.

However, most implementations still depend on laboratory-grade EEG and custom hardware, limiting accessibility. The *Neurophone* addresses this gap by using consumer-grade equipment (Muse S headband), a low-cost mobile app (Mind-Monitor), and a widely available DAW (Ableton Live with Max for Live). This configuration reduces cost, enhances portability, and enables plug-and-play usability, expanding BCMI applications beyond specialized laboratories. In doing so, the *Neurophone* provides a flexible foundation for integrating neurophysiological markers into structured musical frameworks and for advancing transformative paradigms in both research and practice.

III. Methodology

A. System Architecture

This project develops a BCMI for emotional neurofeedback, named the *Neurophone*. The proposed BCMI consists of a wearable EEG system, a mobile preprocessing stage, and a digital audio station (DAW) where real-time musification and feedback are implemented. The overall block diagram is shown in Fig. 1, followed by a detailed description of each module.

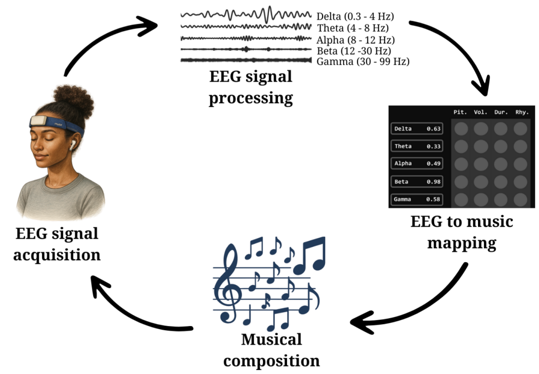

Fig. 1: Block diagram of the proposed Brain-Computer Music Interface (BCMI).

EEG signal acquisition. EEG signals are recorded in real-time using the Muse S headband, which integrates four dry electrodes located at TP9, AF7, AF8, and TP10, with FPz as reference (sampling rate 256 Hz, resolution 12 bits/sample, Bluetooth 5.3, weight 41 g) [29]. Electrode placement is shown in Fig. 2.

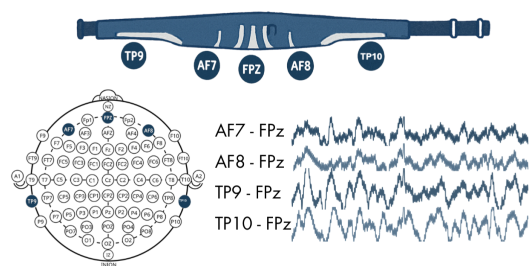

Fig. 2: Electrode placement of the Muse S headband.

EEG signal processing. The acquired signals are transmitted via Bluetooth to the MindMonitor mobile application, which provides real-time data streams and spectral power in the five physiological frequency bands (delta, theta, alpha, beta, gamma) using 1-second windows. Spectral power is computed as:

$$P_{band} = \frac{1}{N} \sum_{n=1}^{N} X_{band}^2[n] \tag{1}$$

where $X_{band}[n]$ is the amplitude of the band-filtered signal at discrete time n, and N is the number of samples per 1-second window [30].

Real-time feature extraction in Max for Live. Once the features are received in the DAW, additional real-time processing is performed in Max for Live. Within each 1-second cycle, the system: (i) applies bandpass filtering to the four EEG channels, (ii) computes spectral power per band and electrode, (iii) derives the Frontal Alpha Asymmetry (FAA) index from AF7–AF8, (iv) calculates the delta power to detect high/low states, and (v) performs the musical mapping. The output MIDI notes are embedded into tonal structures (pentatonic, dodecaphonic, or silence) according to the MUX logic described in Section III.

Real-time definition. As defined by Burns and Wellings, a real-time system must provide results that are both correct and timely [31]. The *Neurophone* performs feature extraction, music generation, and data logging within each 1-second window, ensuring immediate feedback for the neurofeedback loop [32].

EEG-to-music mapping. The mapping interface was developed in Max for Live within Ableton Live [33]. Each EEG frequency band can be assigned to musical parameters: pitch, velocity, duration, and rhythm.

Feedback generation. The resulting music is delivered instantly to the user as auditory feedback. They can choose aspects such as the instrument or musical scale, the system adjusts the output based on EEG activity. This approach allows music to act as transduction of neural dynamics into structures musical feedback

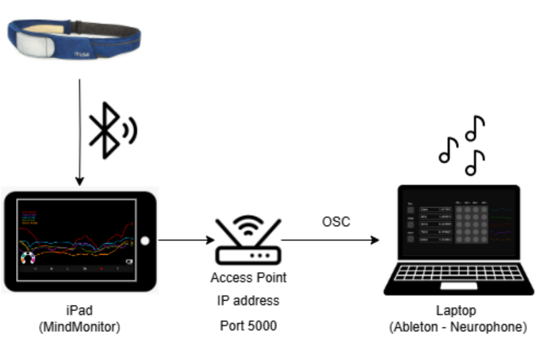

Fig. 3: System connection diagram showing the data transmission between the Muse S headband, MindMonitor (via OSC protocol), and the *Neurophone* patch in Max for Live.

B. Neurophone implementation

The *Neurophone* was developed following a multi-stage process that includes:

a) Data reception: EEG signals are received via OSC from the recording device, then organized into main frequency bands for further processing and mapping.

b) Signal filtering and feature extraction: After acquisition, EEG signals are processed in real time to separate the main frequency bands, which are known to reflect different cognitive and emotional states. From these, the system compute the absolute power providing the basis for both musical parameter mapping and the derivation of higher-level features. In particular, frontal alpha asymmetry, often used as an index of emotional valence [34], [35], is derived from the AF7 and AF8 channels according to:

$$FAA = \log\left(P_{\alpha,\text{AF8}}\right) - \log\left(P_{\alpha,\text{AF7}}\right) \tag{2}$$

Additionally, the frontal delta-band power is estimated, which has been associated in the literature with distinctions between low- and high-activation states [36]. These two features constitute the paradigms employed in the closed-loop feedback design described below.

c) Mapping to musical parameters: EEG features are mapped to musical parameters previously stated, allowing real-time modulation of the output based on fluctuations in brain activity. Each parameter can be linked to one frequency band, while a band may influence multiple parameters simultaneously.

d) Conditional activation logic and parameter scaling: When an EEG band is assigned to a musical parameter, the system applies conditional logic to verify signal validity. Once these conditions are met, the values are mapped onto fixed musical ranges, ensuring reliable detection of EEG activity, consistency across users, and coherence in the resulting output. This process guarantees that values correspond to valid MIDI notes or control signals, maintaining both technical validity and musical structure. To support modularity and clarity, the mapping logic for each frequency band is encapsulated within dedicated submodules.

e) Closed-loop feedback design: The closed-loop uses previously derived neural markers to guide the tonal mode of the feedback, switching between a pentatonic scale, a dodecaphonic scale, or silence. In this way, brain activity is directly linked to structured musical output. Validation of this design will be carried out in future studies integrating EEG recordings with behavioral questionnaires to evaluate measurable neurofeedback effects beyond technical feasibility.

f) Data recording and export: The system includes a recording module that stores synchronized EEG features and musical outputs during each session. Data are exported in structured files with timestamps, frequency band power, and corresponding MIDI events, enabling subsequent analysis of neural activity alongside musical feedback. This integrated workflow ensures that both EEG and musical data are synchronized and readily available for further analysis.

g) User interface design: The interface includes basic fields for participant identification and session tracking, along with real-time visual feedback of the experiment. During data collection, participants complete short questionnaires before and after each session to assess emotional state and subjective experience, providing complementary validation of the neurofeedback process. Analysis of these measures is ongoing and will be reported in future studies.

IV. Results

The *Neurophone* was implemented as a Brain–Computer Music Interface that translates EEG fluctuations into musical output, enabling real-time musification. Fig. 4 illustrates the plugin structure. Its flexible architecture allows the assignment of EEG frequency bands to musical parameters, supporting applications in neuroscience, clinical contexts, and generative art.

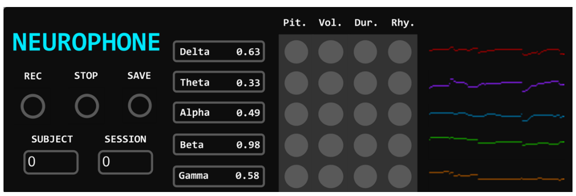

Fig. 4: Overview of the *Neurophone* plugin.

Preliminary tests were conducted in short sessions (3–5 minutes), where alpha, beta, delta, and theta bands were mapped to pitch, velocity, and other parameters. For example, alpha was associated with relaxation (eyes closed), while beta was linked to cognitive engagement (arithmetic tasks). During each session, synchronized EEG, MIDI, and audio data were recorded for subsequent analysis.

As shown in Fig. 5, alpha activity strongly correlated with pitch modulation ($r = 0.88$), confirming that EEG fluctuations can be consistently translated into musical expression. These results demonstrate the system's ability to embed neural dynamics into coherent auditory structures.

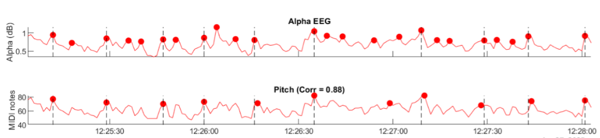

Fig. 5: Real-time mapping of Alpha and Beta EEG bands to pitch and velocity, respectively, using the *Neurophone*. Dashed lines indicate correlation between signals.

Beyond single-band correlations, the closed-loop integrates EEG markers of emotional valence, such as frontal alpha asymmetry and delta power, to dynamically switch between tonal modes (pentatonic, dodecaphonic, or silence; Fig. 6). This mechanism ensures that auditory feedback is not random sonification, but follows organized scales with perceptual salience.

In addition to technical validation, the *Neurophone* addresses key challenges in music-based neurofeedback. Its implementation within a DAW enables rapid prototyping and interoperability, while real-time data logging provides standardized outcome metrics. Moreover, the architecture can be adapted to different EEG devices, broadening accessibility and supporting both artistic use and translational research. By combining EEG-derived markers with structured feedback, the system contributes to ongoing efforts to link brain rhythms with affective states and opens a pathway for future therapeutic applications.

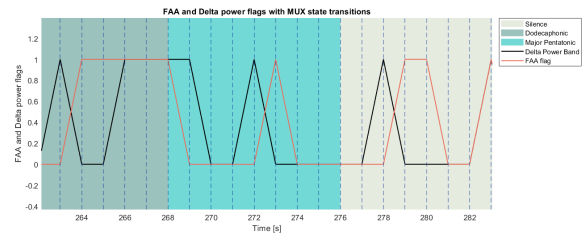

Fig. 6: Real-time monitoring of FAA and Delta power flags driving MUX state transitions.

Fig. 6 illustrates the temporal oscillation of the FAA and Delta power flags, which serve as the inputs to the MUX module. The red and black traces represent the FAA and Delta power flags, respectively, while the colored backgrounds indicate the active MUX state: dodecaphonic (green), major pentatonic (cyan), or silence (gray). Vertical dashed lines mark 1-second intervals, highlighting the temporal dynamics of the transitions. Depending on their joint state, the MUX determines whether the system produces silence, notes within a dodecaphonic scale, or notes within a major pentatonic scale. To avoid abrupt tonal or modal shifts, a buffer stores the last ten outputs of the MUX, ensuring smoother transitions in the generated music. Specific cases can be observed where both flags are simultaneously active, leading to the activation of the pentatonic mode, or where both flags are zero, resulting in silence.

Beyond its technical validation, the *Neurophone* also offers distinctive advantages that address open challenges in the field. The system was designed within a DAW environment (Ableton Live with Max for Live), which not only facilitates rapid prototyping but also allows interoperability with external tools, making it flexible and extensible. The integrated data storage in real-time further enables systematic analysis of EEG dynamics alongside musical output, contributing to more standardized outcome metrics in neurofeedback research. These features make the instrument both user-friendly and adaptable for research or artistic purposes.Audio examples illustrating subject-specific variations in the generated sounds are available at: https://drive.google.com/drive/folders/1GVgoFCL2pmxqlsOZRmmSSXgVwuYE9Ut6?usp=sharing

V. Conclusions

This work presented the design and implementation of the *Neurophone*, a Brain–Computer Music Interface that translates EEG signals into real-time musical output. The system constitutes a low-cost and accessible prototype, enabling sound interaction through brain activity with minimal setup requirements.

At this stage, intentional control is limited, as modulation relies on spontaneous or externally guided EEG activity rather than robust classification or deliberate cognitive strategies. Signal quality and inter-individual variability also affect stability, while thresholds for parameter mapping were tuned for interpretability over expressive flexibility.

Preliminary trials with a single participant confirmed the technical feasibility of EEG-to-music translation but remain exploratory. Rigorous validation as a neurofeedback tool will require structured protocols, baseline recordings, and multi-subject studies.

Future work will focus on controlled user studies to assess usability, perceptual impact, and therapeutic potential, particularly in affective disorders such as anxiety and depression. Technical development may also target a native, open-source plugin to improve accessibility and performance across platforms.

Overall, this research bridges neuroscience and music technology, contributing to the emerging field of neuroadaptive music systems. The *Neurophone* offers a foundation for artistic expression, immersive sound experiences, and potential clinical applications in cognitive training, meditation, and emotional self-regulation.

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