# Csound's Brain: A Real-Time EEG to Harmony, Melody, and Music System for Interactive Performance

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## Abstract

This paper presents a real-time brain-computer interface (BCI) system that moves beyond passive data sonification to prioritize intentional musical control. Developed as a collaborative dialogue between a student researcher and a legacy practitioner, the system maps EEG data from a Muse S Athena headband to melodic and harmonic parameters within Csound. While many BCI systems focus on autonomous generation, our contribution lies in a hybrid control model that uses a sample-and-hold mechanism to 'tame' physiological 'jitter' into a stable, SATB harmonic framework. We demonstrate that this 'Bio-Interactive' approach allows the performer to balance spontaneous internal states with traditional musical intentionality. Through a series of performances - including multi-generational duets - we illustrate how 'Open Source Pedagogy' and mapping transparency can transform raw brainwave data into a deeply personal and expressive musical instrument.

## Keywords

EEG, Csound, OSC, MIDI, Sonification, Brainwave Music, Muse Athena, Mind Monitor, Intentionality, Bio-Interactive Performance, Hybrid Control, Open Source Pedagogy

## 1 Introduction

Physiological signals can serve as both data inputs and sources for musical control. This project asks: Can brainwave activity become a playable musical structure? While the technical foundation of the system rests on the second author's 45-year development of Csound-based BCI tools - rooted in his work with Max Mathews and Pauline Oliveros - the current iteration was driven by the first author's artistic challenge. The first author pushed the system to move beyond 'data sonification' toward 'musicality,' focusing on the emotional resonance of specific frequency bands to create a controllable, expressive instrument.

This research is ultimately driven by the first author's personal experience with the "silence" of dementia. Observing the loss of verbal communication in a loved one sparked a pivotal inquiry: can bio-interactive music serve as a surrogate voice for those trapped within an inner silence? By using Csound to translate EEG fluctuations into a stable SATB harmonic framework, we aim to demonstrate that even when cognitive pathways are obscured, the mind's internal musicality persists, offering a new medium for empathetic connection.

## 2 Historical Lineage and Related Work

The development of Csound's Brain is a direct continuation of the second author's work with Oliveros at the University of California, San Diego (UCSD). During his doctoral studies under the supervision of F. Richard Moore, the author served as a Research Assistant at the Center for Music Experiment (CME) and the Computer Audio Research Laboratory (CARL). In this capacity, the author assisted Oliveros in realizing technically demanding works such as *The Wheel of Time* for the Kronos Quartet. This collaboration involved designing custom sound palettes to Oliveros's specifications using Moore's CMUSIC language. Central to this era was the second author's hosting of *Sonic Meditation* performances, which pioneered the use of bio-reflexivity and focal attention as musical practices. Csound's Brain translates these philosophies into a modern BCI framework, moving toward a "Deep Listening" interaction in which EEG data serves as a conduit for the performer's internal state. The use of EEG data as a generative musical source has a rich history within the NIME and experimental music communities. This work follows in the footsteps of pioneers such as Alvin Lucier, whose *Music for Solo Performer* (1965) [19] utilized alpha waves to physically vibrate percussion instruments, marking the first major intersection of brain activity and acoustic performance. Similarly, Pauline Oliveros's *Sonic Meditations* (1971) [22] emphasized the role of deep listening and internal states in musical creation, a philosophy that informs our system's focus on 'listening to the internal self.

Technically, our system builds upon the sonification strategies explored by Rosenboom [26] and more recently by Miranda et al. [20], who used BCI interfaces to trigger MIDI events and control generative algorithms. However, while previous works often focused on mapping data to abstract timbres, our research focuses on a harmonic 'taming' process. By using a four-part (SATB) harmonic framework within Csound, we prioritize the musicality of the output, ensuring that the EEG data is not just 'heard' as a signal, but 'performed' as a melodic dialogue.

### 2.1 From Gestural to Physiological Control (The Mathews Lineage)

The mapping strategies employed in Csound's Brain represent a direct evolution of the gestural control philosophies pioneered by Max Mathews and the second author. Specifically, this work builds upon the 'conductor-program' paradigm of Mathews' Radio Baton, which the second author premiered at NIME 2003 (Montreal) in works such as *StarDust* and *DarkMatter*. Where the Radio Baton used spatial $(x, y, z)$ coordinates to trigger and shape Csound events,


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the current system replaces physical mallets with EEG-derived frequency bands. We argue that the Gamma and Alpha fluctuations in the cortical signal function as 'internal gestures,' requiring the same level of instrumental 'taming' and mapping transparency as the physical strikes of a Baton. By transitioning from the gestural to the physiological, we continue Mathews' vision of making the computer a truly 'playable' instrument, shifting the site of expression from the hand to the mind while maintaining a rigorous, real-time connection between the performer and the synthesis engine.

## 3 System Overview

The system architecture (see Figure 1) facilitates a real-time data pipeline from cortical activity to synthesis. It uses the *Muse S Athena* EEG headband and the *Mind Monitor* application as the acquisition front end, with Csound serving as the real-time audio engine.

### 3.1 Device and Signal Acquisition

The Muse S Athena is a 7-channel wearable EEG device. For this system, we focus on the four passive EEG sensors (TP9, AF7, AF8, TP10), which provide a stable view of frequency band fluctuations. While signal integrity depends on sensor-to-skin adhesion, the system uses Csound-based filtering to mitigate transient spikes. These hardware configurations and stable contact protocols have been refined through over 30 years of sensor workshops at Berklee College of Music, ensuring a reliable baseline for creative expression without requiring specialized medical-grade preparation.

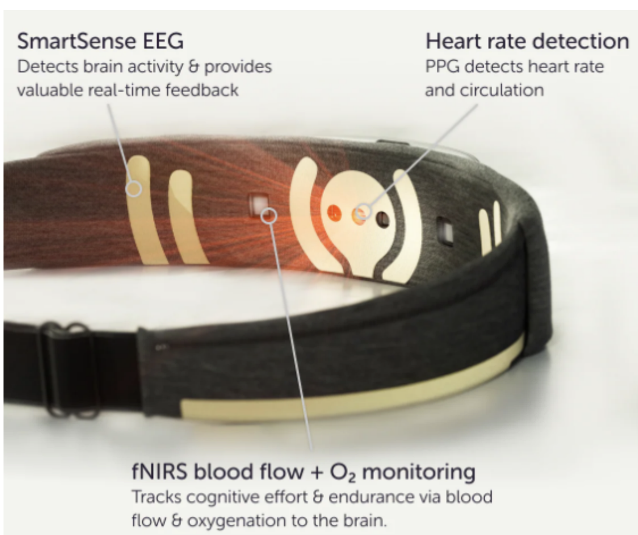


**Figure 1: The Muse S Athena EEG and fNIRS Headband.**

### 3.2 OSC Streaming and Connectivity

The system utilizes the Muse S (Gen 2) Athena headband, which provides four channels of EEG data via dry-electrode sensors at positions TP9, TP10, AF7, and AF8 (International 10-20 System). By focusing on these frontal and temporal lobes, the Csound engine can reliably distinguish between the 'focal attention' signals in the pre-frontal cortex and the 'meditative' alpha rhythms typically associated with the temporal regions.

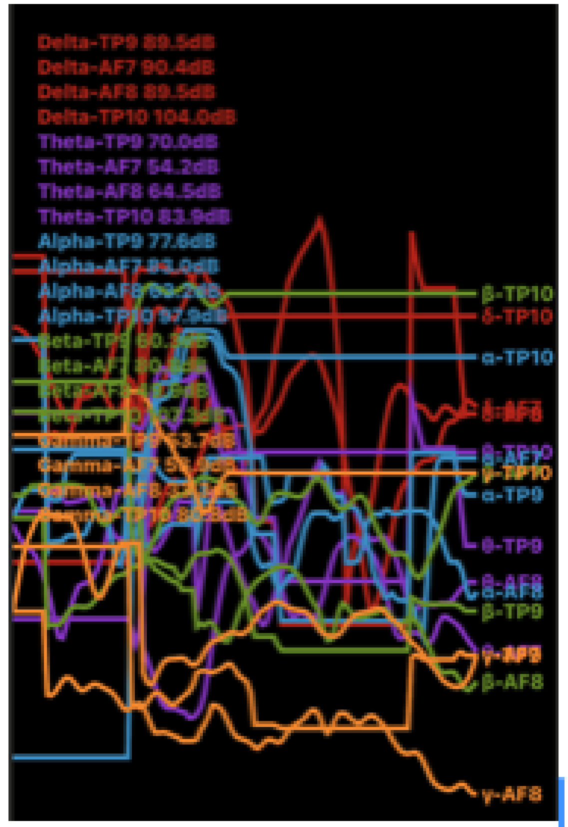


**Figure 2: Mind Monitor waveform and band values during a stable connection.**

**Table 1: Characteristics of EEG Frequency Bands in Mind Monitor**

| Band (Color) | Typical State and Characteristics |
|---|---|
| **Delta** (red) | Lowest frequency; indicates states of deep sleep or profound relaxation. |
| **Theta** (purple) | Common during light sleep, meditation, and states conducive to memory recall or intuition. |
| **Alpha** (blue) | Occurs during relaxed yet alert states, such as resting with eyes closed; indicates calmness and stability. |
| **Beta** (green) | Linked to task-focused thinking, judgment, and sustained attention; can increase with tension or excitement. |
| **Gamma** (orange) | Highest frequency; describes high-intensity information integration and highly focused processing. |

Data transmission is handled via the Open Sound Control (OSC) protocol over a local Wi-Fi network. Mind Monitor scales and transmits absolute frequency-band data to a target IP address. To ensure low-latency performance - crucial for the "feel" of live interaction - the system requires a dedicated network environment to minimize jitter. Once established, this data link provides five continuous numerical streams that serve as the generative seeds for the Csound engine.

## 4 Implementation and Open Source Pedagogy

In the spirit of Open Source Pedagogy, one of the complete Csound *".csd"* files is provided here (see Listing 1), based on the FLOSS manual [15], to ensure reproducibility and provide a foundational framework for other student researchers. By documenting the exact mapping logic between OSC-streamed EEG data and Csound's synthesis engine, we aim to lower the barrier for interdisciplinary collaboration [18] between neuroscience and computer music.

```
<CsoundSynthesizer>
<CsInstruments>

; Header Section
sr     = 44100  ; audio or sample rate
ksmps  = 100    ; control rate
nchnls = 2      ; stereo
0dbfs  = 1.6    ; max amplitude

; Global Initialization
schedule 1, 0, -1       ; Start OSC Monitor
schedule "revsc", 0, -1  ; Start Reverb

; Waveform Definitions
giSine   ftgen 1,0,16384,10, 1
giSquare ftgen 2,0,16384,10, 1,0,.33,0,.2,0,.14,0,.11,0,.09
giSaw    ftgen 3,0,16384,10,
      1,.5,.3,.2,.1,.06,.04,.028,.010
giFour   ftgen 4,0,16384,10,
      1,.2,0,.4,0,.6,0,.8,0,1,0,.8,0,.6,0,.4,0,.2
giFive   ftgen 5,0,16384,10,
      1,0,0,.6,0,0,.5,0,0,.4,0,0,.3,0,0,.2,0,0,.1
giAmy    ftgen 6,0,16384,10, 7,23,11,10,9,5,8,12,26,14 ;
      First Author Design

gaRvbL init 0
gaRvbR init 0

gkF1 init 0
gkF2 init 0
gkF3 init 0
gkF4 init 0

; SATB Chord Tables
giSoprano ftgen 111,0,4,-2, 62,60,55,71
giAlto    ftgen 112,0,4,-2, 59,57,60,62
giTenor   ftgen 113,0,4,-2, 52,52,55,59
giBass    ftgen 114,0,4,-2, 36,41,40,43

instr 1 ; OSC Stream Reader
giHandle OSCinit 5003
kk OSClisten giHandle,"/muse/elements/delta_absolute","ffff
      ",gkF1,gkF2,gkF3,gkF4
endin

instr 2 ; Synthesis and Mapping Logic
iNum notnum
iTrans = (exp(log(2.0)*((iNum)-69.0)/12.0))

; Map Controllers
kGainC   midic7 21, 0, 1
kSpeedC  midic7 22, .05, 3
kTrigC   metro kSpeedC

; Sample and Hold Brainwave Data
kFvalC   samphold gkF2, kTrigC
kFvalC   = kFvalC * 10000
kIndexC  = int(abs(kFvalC)) % 4

; Table Lookup
kPitch1  table kIndexC, giSoprano
kPitch2  table kIndexC, giAlto
kPitch3  table kIndexC, giTenor
kPitch4  table kIndexC, giBass

; Audio Output
aOut1  oscili (0.3*kGainC), (iTrans)*cpsmidinn(kPitch1),
      giAmy
aOut2  oscili (0.4*kGainC), (iTrans)*cpsmidinn(kPitch2),
      giSquare
aOut3  oscili (0.5*kGainC), (iTrans)*cpsmidinn(kPitch3),
      giFour
aOut4  oscili (0.6*kGainC), (iTrans/2)*cpsmidinn(kPitch4),
      giSaw

; Reverb Sends
gaRvbL += aOut1 * 0.4
gaRvbR += aOut2 * 0.4
outs aOut1, aOut2
endin

instr revsc
aOutL, aOutR reverbsc gaRvbL, gaRvbR, 0.8, 8000
outs aOutL, aOutR
gaRvbL = 0
gaRvbR = 0
endin

</CsInstruments>
</CsoundSynthesizer>
```

**Listing 1: Full Csound Orchestral Implementation.**

### 4.1 Mapping Strategy and Performance Control

A primary challenge in BCI is the "jitter" of raw EEG. To resolve this, we employ a hybrid control model. While a MIDI keyboard serves as the performance anchor for transposition and phrasing, the EEG data is managed via a sample-and-hold mechanism. As shown in Listing 1, the metro opcode generates trigger pulses at a rate defined by the performer. At each pulse, the sample-and-hold captures a snapshot of the brainwave streams from each of the four channels (e.g., Gamma for melody). These values are scaled and used as an index for the SATB (Soprano, Alto, Tenor, Bass) chord tables. This transforms chaotic physiological fluctuations into stable, musically coherent events.

**Table 2: Mapping of EEG Frequency Bands to Csound Musical Parameters**

| Frequency Band | EEG State | Musical Role in Csound |
|---|---|---|
| **Delta** ($\delta$) | Deep Sleep/Rest | Foundational Texture / Bass Density |
| **Theta** ($\theta$) | Meditation/Intuition | Harmonic Complexity / Inner Voices |
| **Alpha** ($\alpha$) | Calmness/Stability | Global Volume / Spatial Breadth |
| **Beta** ($\beta$) | Focused Thinking | Rhythmic Density / Trigger Speed |
| **Gamma** ($\gamma$) | High Processing | Melodic Indexing / Timbral Brightness |

## 5 Implementation: Redesigning for Focus and Agency

In response to the first author's initial observations - specifically, that the system lacked a dramatic, distinct "signature" for different users - the Csound architecture was re-engineered. The goal shifted from mapping all data to providing a filtered, intentional musical output.

### 5.1 Discrete Mapping and SATB Framework

To address the "sameness" of the output, we replaced continuous modulation with a Sample-and-Hold logic.

**The Challenge:** The first author noted that the brainwaves felt "buried" in the math.

**The Solution:** We designed specific chord tables (giSoprano, giAlto, etc.) and melodic patterns that only update when triggered. This creates the "focus" the first author requested - allowing the performer to hear exactly how a change in thought selects a new chord or a specific melodic fragment.

### 5.2 The Performer's Interaction Layer

The MIDI keyboard was redefined not just as a trigger, but as a contextual filter:

**Start/Stop Phrasing:** The performer uses keys to define the temporal "shape" of the brain's "singing."

**Control Intersections:** MIDI CC knobs now act as "intersections" where the performer chooses how much the brainwave data is allowed to perturb the pattern. This turns the system into a dialogue: the brain provides the "seed," but the performer provides the "musical intent."

### 5.3 The Performer as Intermediary: Playing "The Other"

Originally designed for solo exploration, the system was redesigned into a multi-agent framework during rehearsal. We discovered that the most profound musicality occurred when the "source" (the brain) and the "performer" (the hands) were decoupled.

**The Switch:** In our recent experiments, the roles are reversed: Shiying plays Dr. B's brainwaves, and Dr. B plays Shiying's.

**The Dialogue:** This creates a "Bio-Jazz" environment. Shiying uses her sense of melody to "tame" Dr. B's conservatory-style harmonies, while Dr. B responds to the rhythmic patterns generated by Shiying's cognitive state. The dialogue is no longer between a human and a computer, but between two humans via a shared physiological and digital bridge.

## 6 Reflective Practice: A Longitudinal Case Study

The implementation process served as a primary site for pedagogical reflection. The first author initially approached the Csound environment as a daunting 'wall of math.' However, through the collaborative 'taming' process described in Section 4, she transitioned from technical apprehension to a state of musical intentionality. By redesigning the modern harmonies to be more personally resonant, the first author discovered that she could effectively 'play' another person's internal state, effectively finding a new mode of dialogue that transcends verbal communication.

The first author noted that "When we rehearsed for our concerts, there was a moment where Dr. B stepped away, and I began playing both keyboards - effectively playing both our minds at once. It felt like we were finding something new about each other that words couldn't reach. It's like being two jazz musicians improvising; I'm listening to what his brain is doing, he's listening to what mine is doing, and we are meeting in the middle. This discovery - that we could switch 'brains' - is what we want to share. It brought us so much joy because it turned a technical experiment into a deep, human connection." (See figure 6.)

**Figure 3: The Spontaneous Genesis of the Duet concept.**

### 6.1 Phenomenological Observations: From Math to Music

Initially, the first author expected the system to be a purely abstract exploration of data. However, as the synthesis began, the technical complexity dissolved into a visceral awareness. Hearing one's internal state take the form of sound shifts the experience from 'monitoring' to 'singing.' This creates a profound existential inquiry: when the mind is heard as music, the boundaries between the digital and the biological blur.

As the first author noted, "There is a unique, almost indescribable awareness that comes from hearing your own internal state take the form of sound. It feels as though your thoughts are gaining a physical shape or manifesting as a voice. It shifts the experience from 'monitoring a system' to realizing that 'your body can sing.' This creates a profound existential inquiry: hearing your own mind as music forces you to confront the question, 'Who am I?' in a way that words or numbers cannot capture."

### 6.2 Methodological Iteration: Personalizing the Data

Following the initial discovery, the first author tested the system across diverse contexts: during focused study sessions, states of rest, and through the observation of family members' brainwaves. The goal was to quantify how patterns shifted across different emotional states. However, a limitation was identified: despite profound changes in the physiological source, the musical output initially lacked distinct 'signatures.' This led to a pivotal research question: how can the system connect more deeply to the individual? The first author challenged the second author to move beyond a static harmonic framework, resulting in a more 'porous' design where Beta and Gamma waves create a unique timbral signature for each user.

### 6.3 Evaluating Systematic Agency and 'Truth'

The collaborative refinement process was driven by a need for 'systemic truth' - the requirement that the music feel authentically representative of the performer's state. When the first author noted a sense of disconnection, it sparked a complete architectural rethink. By transitioning from complex, automated equations to a focused, manually-anchored chordal system, the interface began to function as a true instrument. The first author observed that she was no longer merely 'watching' data, but actively interacting with it, feeling the moment her cognitive intent intersected with the Csound code. This shift confirmed that for a BCI system to be successful, the performer's mind must be in sync with the musical logic.

### 6.4 Case Study: The Multi-Generational Dialogue

Performing alongside her younger brother, Gorden, allowed the first author to explore the system's social transparency. While she remained focused on the technical control of the Csound melodies, she observed a shift in the musical 'gravity' as the system began to map the internal state of a loved one.

As the first author reflects: "There was a moment where the music caught Gorden's own attention - he looked up and smiled, as if he finally 'heard' himself. In that moment, the system wasn't just an interface; it was a bridge." This suggests that the technology can facilitate a new kind of social connection [8] that transcends mere sound-making.

**Figure 4: The "Aha!" Moment: Gorden Chen looks upward with a profound sense of awareness and understanding in control of his musical mind - "That's the sound of me!".**

## 7 Experience and Reflections: A Bio-Meditative Lineage

This system represents the state of the art in a 35-year practice in bio-interactive performance, rooted in the pedagogical and artistic traditions of Deep Listening and Sonic Meditations.

**Historical Continuity:** The design is deeply influenced by the first author's work with mentor and collaborator Pauline Oliveros, a pioneer in brainwave music and meditative biofeedback. By grounding the Csound engine in Oliveros's philosophy, the system moves beyond data sonification and toward a "Deep Listening" practice, where the performer must become acutely aware of their internal physiological state to "play" the resulting harmony. The system's "stability" (the sample-and-hold logic) is designed to facilitate the same heightened state of awareness required for a Sonic Meditation. The performer, using the Muse-to-Csound system, feels less like "triggering notes" and more like the active listening and focal attention practiced in the Quonset huts of UCSD's Center for Music Experiment (CME) by Oliverso, Boulanger, and small groups of graduate students.

**Longitudinal Pedagogy:** Drawing on over three decades of brainwave performance - from early sensor workshops at Berklee College of Music in the 1990s to recent keynotes at ICSC 2019 in Italy [5] and ICSC 2022 in Ireland [9] - several qualitative "feelings" emerge regarding the stability and "playability" of the system.

**Collaborative Refinement:** Through an iterative design process, the authors refined the interface's 'playability.' By grounding the system in a Satie-esque SATB framework, the first author found that the stability of the harmony enabled a state of 'recursive bio-reflexivity,' in which the music informs the performer's mental state, which in turn reshapes the music.

**Accessibility and Connection:** Recent workshops in Irvine, California (2025-2026) and concert performances there - such as the first author playing her brother Gorden's brainwaves. demonstrate that the system can foster a unique empathetic connection between the "listener" and the "source."

**Figure 5: Sibling Duet: The first author and her brother Gorden performing.**

## 8 Lineage and Collaborative Reflections

This work is a synthesis of legacy and new inspiration. The system's philosophical roots trace back to the second author's work as a Research Assistant at the Computer Audio Research Laboratory (CARL) at UCSD, assisting Pauline Oliveros in realizing *The Wheel of Time* for the Kronos Quartet and hosting *Sonic Meditations.*

However, the current iteration is defined by the first author's role as a catalyst. Shiying Chen challenged the system to move beyond the "interesting" randomness of raw EEG, pushing for a direct sense of musical agency. This led to refinements in frequency band mapping (e.g., using Gamma for melodic indexing) and the integration of MIDI-anchored control. The results, evidenced in recent performances including the BrainWave Duet (Irvine, 2025) and sessions involving family members, show a move toward a deeper, more empathetic connection between the "performer" and the "instrument."

The current iteration of the system is the result of a symbiotic dialogue between a legacy practice and a fresh artistic challenge.

**The Catalyst for Musicality:** The first author served as the primary "muse" and critic, challenging the second author to move beyond the technical "interestingness" of early BCI experiments. Her focus has been on intentionality and control - refining how specific EEG frequency bands map to tonal development and melodic themes.

**Refining the Connection:** Together, the authors have focused on the "feel" of the connection. Whereas previous work was often experimental or chaotic, the current system strives for a direct link between the performer's emotional state and the temporal and timbral development of the musical output.

**Future Iterations:** The authors are continuing to expand the system's versatility across genres, exploring how BCI can control more than just pitch - specifically, focusing on developing theme and time-based structures that allow for a more traditional sense of musical "growth."

Today, the system serves as a foundation for deeper bio-interactive performance research. Future work will focus on three primary areas of development:

**Direct API Integration:** We are developing a custom Muse API bridge to bypass intermediary apps like Mind Monitor, reducing latency and allowing for more granular control over the raw EEG data streams.

**Hardware Expansion:** Integration with OpenBCI [25] hardware and the OpenBCI GUI [24] is underway to allow for higher electrode density, providing more complex spatial mapping of brain activity to Csound parameters.

**Generative Accompaniment:** We are exploring algorithmic "ensemble" voices that use generative logic to respond to the performer's brainwave fluctuations, creating a more dynamic and unpredictable musical dialogue.

## 9 The Bio-Interactive Paradox: Who is the Composer?

The transition to "Brainwave Duets" raised profound existential and psychological questions that define the current research focus. When the first author performed using the second author's brainwaves, a "feedback loop of intent" emerged:

**The Influence Question:** "Am I making him think differently because of my control?" The first author observed that her musical choices - taming harmonies or changing melodic speed seemed to provoke new patterns in the source brainwaves.

**The Interpretation Question:** "Is it how he's thinking I'm playing, or is this what my playing is making him think?" The performers experienced a blurring of boundaries, making it impossible to distinguish whether the music reflected the performers' internal states or reacted to their external stimuli.

**The Empathy Gap:** This dialogue mirrors the "honesty" of a deep conversation. Just as one might react to a misunderstood joke, the brainwaves reacted to "misplayed" musical phrases, creating a transparent, honest dialogue that suggests bio-interactive systems can function not just as instruments, but as prosthetic extensions of human empathy.

## 10 Supplemental Media and Documentation

A curated collection of "Sonic Meditation" excerpts, performance photos, and pedagogical shorts (including the BrainWave Duet and "Gorden's Brain" sessions) is hosted at richardboulanger.com. These resources illustrate the transition from raw EEG data to a refined, collaborative musical experience.

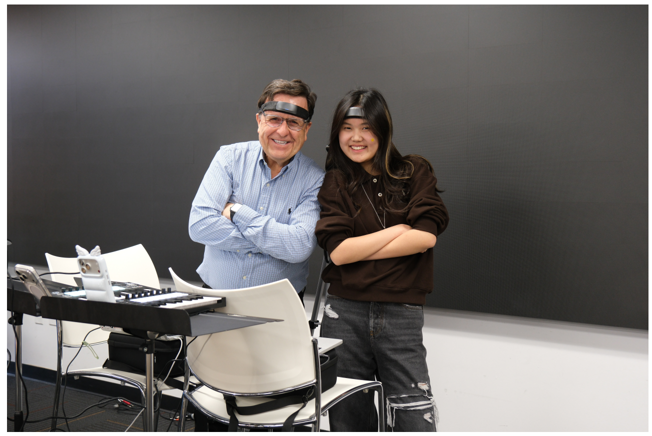

**Figure 6: The Joy of Bio-Interactive Music: Shiying (Amy) Chen and Dr.B following their final dress rehearsal for the Irvine concert. Both performers are wearing Muse S Athena headsets and have successfully calibrated the "Brainwave Duet" system. This image captures the personal and artistic fulfillment found in moving from technical debugging to a shared, expressive musical dialogue. "We're good to go. Let's make some music!"**

## 11 Ethical Standards and Copyright

This paper presents a system design and implementation; no human subjects research was conducted. Development was conducted at the authors' respective institutions and homes, without external project-specific funding. The participation of the first author's minor sibling was conducted with full parental consent and served as an informal pedagogical demonstration of the system's accessibility. **The system is open-source software released under the GNU Lesser General Public License (LGPL) version 2.1 or later.** The authors declare no conflicts of interest. **This work is licensed under a Creative Commons Attribution 4.0 International License (CC BY 4.0).**

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