

The *Hyper-Neurophone*: Coupling Inter-Brain Synchronization and Real-Time Neural Visualization in Collaborative Musical Performance

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Abstract—This paper introduces a novel Brain-Computer Music Interface (BCMI) called the *Hyper-Neurophone*. Building upon an individual emotional neurofeedback system, this evolution proposes a distributed, dyadic framework designed to couple inter-brain synchronization (IBS) and real-time neural visualization during collaborative musical performance. Utilizing the Internet of Musical Things (IoMusT) as conceptual infrastructure, the pipeline streams raw electroencephalographic (EEG) data from two concurrent Muse S headbands into a centralized browser-based acquisition application. These raw streams are forwarded locally to a heavily modified processing module that handles multi-channel digital filtering, feature extraction, and local logging before distributing Frontal Alpha Asymmetry (FAA) indices and relative power via OSC to a TouchDesigner visualization engine. Rather than assuming a single linear state, we hypothesize that the continuous visual mapping of beta-band activity acts as a shared neural mirror, triggering distinct neurophysiological adaptations when direct eye contact is unavailable. Preliminary results from pilot sessions support this, showing significant cross-brain connectivity modulations characterized either by global phase alignment or complementary leader-follower dialogs. Finally, we discuss the system architecture, multimodal mappings, and open challenges for distributed network deployment in remote environments.

Index Terms—Brain-Computer Music Interfaces (BCMI), Electroencephalography (EEG), Inter-brain synchronization (IBS), Real-time visualization, Interactive multimedia, Internet of Musical Things (IoMusT), Collaborative musical performance.

I. INTRODUCTION

The intersection of neuroscience and music technology has led to the development of Brain-Computer Musical Interfaces (BCMI), enabling sound modulation driven by cortical activity [1]. Traditionally, these interfaces have focused on individual users; however, human brain function and music are intrinsically social phenomena [2]. The transition toward multi-user

systems represents the next evolutionary step in this discipline, providing a robust framework for studying human interaction at a deep neurophysiological level through the lens of second-person neuroscience [3].

The paradigm of hyperscanning has revealed that social coordination is fundamentally mediated by the synchronization of neural oscillations across brains [4]. In musical improvisation, where musicians respond to their partners with millisecond precision, this inter-brain synchrony (IBS) is critical [5]. Studies utilizing EEG hyperscanning have consistently demonstrated dynamic orchestration and robust intra- and inter-brain synchronization during collaborative, free-flowing musical execution [6], [7].

Despite these insights, measurable neural synchrony is predominantly observed during physical co-presence. In current technological contexts characterized by increasing virtuality, remote musical execution presents significant challenges due to inherent network latencies [8]. Mediated environments often suffer from the loss of crucial non-verbal communicative cues that extend beyond mere sound [8]. Therefore, this study investigates alternative methodologies for measuring and visualizing the degree of neural synchronization between musicians under virtual conditions. Drawing upon emerging evidence that IBS can occur without physical co-presence and can be enhanced through remote joint attention tasks [9], this research explores real-time visual feedback modalities to bridge the gap in disembodied, remote musical collaboration.

The remainder of this paper is organized as follows. Section II reviews the relevant background on BCMI and inter-brain synchronization in musical performance. Section III details the methodology, including the experimental protocol, system architecture, and feature computation. Section IV presents the results and discussion of the dyadic neurophys-

iological interaction, and Section V outlines our conclusions and avenues for future work.

II. BACKGROUND

The application of BCMI has garnered significant research interest, largely driven by the understanding that human brain function is intrinsically social [2], [3]. Hyperscanning studies demonstrate that collaborative musical tasks generate robust IBS, irrespective of physical co-presence [10]. Crucially, dual-EEG evidence reveals that this neural coupling is not merely an epiphenomenon of shared auditory input or motor responses; rather, it reflects top-down endogenous cognitive processes—such as joint attention, temporal planning, and mutual adaptation—essential during challenging musical coordination [4], [11]. This phenomenon extends into clinical domains, where directional neural synchrony acts as a physiological marker of empathy and active information transfer [9].

A substantial body of research has focused on identifying synchronization patterns related to affective processing, as emotional valence and intensity strongly influence IBS in neural regions associated with aesthetic appreciation [9]. To harness this within BCMI development, feature extraction methods achieve high detection accuracies ($> 85\%$) for discriminating emotional arousal and valence using connectivity features like Magnitude Square Coherence [1]. This real-time emotional and synchronous tracking has been implemented in dual-brain systems like BrainiBeats and EmoLoop, which utilize metrics such as Frontal Alpha Asymmetry (FAA) and Phase Lock Values (PLV) to continuously modulate musical elements based on shared affective states [12], [13].

Furthermore, collaborative execution reveals intricate, dynamic neural architectures. In score-based performances, IBS significantly increases in specific frequency bands when musicians face unfamiliar parts, indicating heightened mutual prediction [11]. Similarly, empirical studies of free improvisation in guitar duets have identified extended hyper-brain networks and cortical phase-locking asymmetries that reliably discriminate musical leaders from followers [5], [14]. These documented synchronization patterns present a unique opportunity to transpose neural tracking into technologically mediated spaces, such as the BCHJam ecosystem [15]. However, utilizing synchronous data as active, real-time visual feedback directed at the performing musicians themselves remains largely unexplored. Implementing explicit feedback modalities based on IBS could serve as a vital source of relational information, compensating for communication limitations inherent to disembodied or virtual performance environments [16].

III. METHODOLOGY

A. Experimental Protocol

The proposed framework was evaluated during a collaborative musical performance involving two musicians, each equipped with a Muse S Athena EEG headband, interpreting the same piece under two interaction conditions. In the first condition (se01), musicians maintained conventional visual contact (Fig. 1). In the second condition (se02), performers

avoided direct eye contact and relied exclusively on a shared visual representation of their neural activity generated by the *Hyper-Neurophone* platform (Fig. 2), assessing the feasibility of using neural visualization as an alternative interaction channel. Both conditions preserved the same collaborative musical task and EEG acquisition pipeline, isolating the available interaction channel as the primary experimental variable.

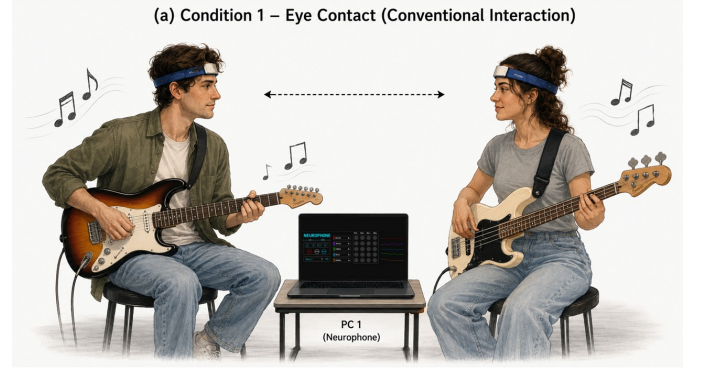


Fig. 1. Communication pipeline summarized.

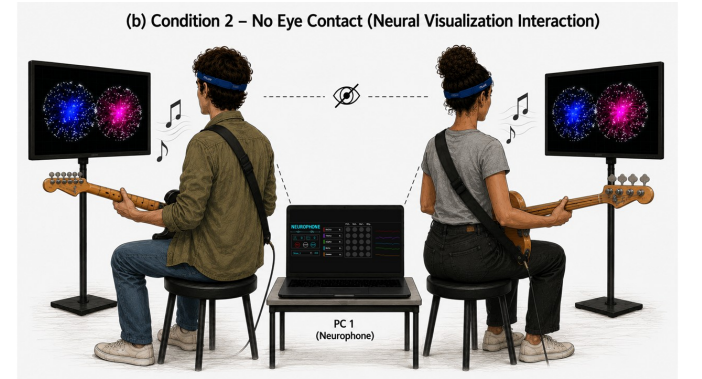


Fig. 2. Communication pipeline summarized.

B. System Architecture

The *Hyper-Neurophone* platform follows a modular architecture separating neural data acquisition, digital signal processing, and visual rendering into independent, decoupled software components to ensure real-time synchronization (Fig. 3).

The data pipeline operates sequentially across three distinct stages:

- 1) **Data Acquisition:** Raw EEG streams are captured from both performers concurrently via a centralized acquisition client.
- 2) **Neural Processing Module:** The raw streams are forwarded locally to a heavily modified, dyadic evolution of the *Neurophone* system—originally introduced as an individual emotional neurofeedback BCMI by Velasquez-Pena et al. [17]. This updated module performs multi-channel digital filtering, features extraction, and logs the processed variables prior to external transmission.

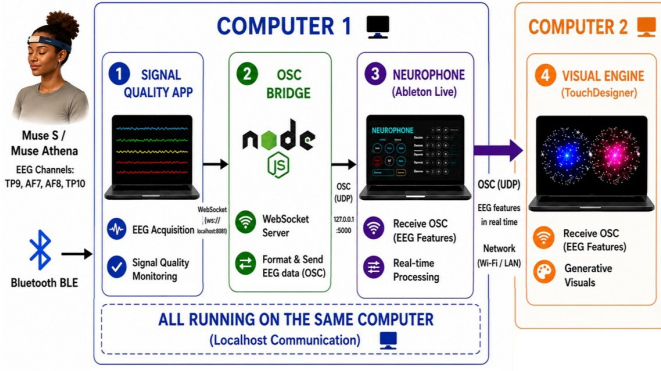


Fig. 3. Overall architecture of the *Hyper-Neurophone* platform. The system is composed of two interconnected computers.

- 3) **Visual Interface:** The extracted and filtered neural descriptors are distributed through an OSC-based communication layer to a customized TouchDesigner visualization engine for real-time interactive multimedia rendering.

C. EEG Acquisition Application

The application constitutes the entry point of the pipeline, responsible for establishing Bluetooth connections with the headbands and managing initial packet streaming. Implemented as a browser-based client (React/TypeScript), it leverages the Web Bluetooth API via the `eeg-web-ble` library, defining two independent connection slots to support concurrent dyadic streaming without cross-interference. Raw EEG frames are decoded via WebAssembly and demultiplexed into four channels (TP9, AF7, AF8, TP10). For local signal-quality inspection, a filtered copy—processed via a cascade of high-pass (0.5 Hz), low-pass (58 Hz), and notch (60 Hz) IIR biquad filters—is rendered over a 3-second sliding window. Critically, to preserve signal integrity for downstream analysis, the unfiltered raw samples are packaged into JSON messages and forwarded over a local WebSocket connection to the modified processing module.

D. Modified Processing Module and Feature Computation

The core processing hub consists of a customized evolution of the *Neurophone* architecture [17], re-engineered to handle two simultaneous EEG streams within an Ableton Live 11 environment via Max for Live. Upon receiving the raw data, this module applies a dedicated filtering stage tailored for spectral analysis.

Following digital filtering, the module continuously estimates absolute band power, relative band power, and Frontal Alpha Asymmetry (FAA), logging all computed descriptors locally before formatting them into standardized OSC messages. Absolute band power quantifies the spectral energy within a specific frequency band:

$$P_{abs}^{(b)} = \int_{f_l}^{f_h} PSD(f) df \quad (1)$$

TABLE I
EXPERIMENTAL CONFIGURATION OF THE *Hyper-Neurophone* PLATFORM.

Component	Specification
EEG Device	Muse S Athena
Electrodes	TP9, AF7, AF8, TP10
Sampling Frequency	256 Hz
Acquisition Module	<i>Hyper-Neurophone</i> App
Processing Module	Neurophone (Max for Live)
Communication	Bluetooth BLE, WebSocket, OSC/UDP
Visualization Engine	TouchDesigner 2025.309
Audio Environment	Ableton Live 11

where $PSD(f)$ denotes the power spectral density. Relative band power normalizes this energy with respect to the total spectral power to mitigate inter-subject variability:

$$P_{rel}^{(b)} = \frac{P_{abs}^{(b)}}{\sum_{k=1}^N P_{abs}^{(k)}} \quad (2)$$

Relative beta power ($P_{rel}^{(b)}$) serves as the primary variable driving the visual interaction. Additionally, FAA is computed from the alpha-band over frontal electrodes for offline affective analysis:

$$FAA = \log(P_{\alpha}^{AF8}) - \log(P_{\alpha}^{AF7}) \quad (3)$$

E. Shared Neural Visualization

The visual interface was developed in TouchDesigner using particle operators (POPs). Two dynamic particle structures with stochastic radial expansion, motion trails, blur effects, and color transformations produce a neuron-synapse appearance (Fig. 4). Each structure represents one participant (left/blue and right/red). The $P_{rel}^{(b)}$ transmitted from the processing module controls an attractive force driving the particles toward the center of the visualization. Simultaneously, $P_{rel}^{(b)}$ modulates the color through interpolation in the RGB space, maintaining a constant green channel while varying red and blue channels, causing both structures to converge toward purple hues as activation increases. This spatial and color convergence serves as a visual metaphor for the alignment of the musicians' neurophysiological states.

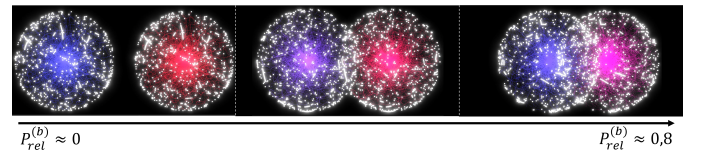


Fig. 4. Evolution of the particle-based visualization driven by the $P_{rel}^{(b)}$ of two participants

F. Experimental Setup

The platform was distributed across two computers to prevent computational interference. The first computer hosted the EEG acquisition app and the modified *Neurophone* processing module, while the second executed the TouchDesigner

TABLE II
CROSS-BRAIN PEARSON CORRELATION RESULTS ACROSS EXPERIMENTAL CONDITIONS

Dyad	Condition	Delta (R)	Theta (R)	Alpha (R)	Beta (R)	Gamma (R)
SU00	Hyper-Neurophone	+0.0579*	+0.0441*	+0.0367*	+0.0330*	-0.0044
SU00	Visual Contact	-0.0252	-0.0176	-0.0105	-0.0171	+0.0137
SU01	Hyper-Neurophone	-0.0164	-0.0984*	-0.0486*	-0.0522*	-0.0240
SU01	Visual Contact	+0.0793*	+0.0108	-0.0010	-0.0071	+0.0026

Note: * indicates statistical significance with $p < 0.01$.

environment, receiving the processed features via OSC/UDP. Table I summarizes the configuration employed throughout the sessions.

IV. RESULTS AND DISCUSSION

The preliminary experimental results offer encouraging insights that support the hypothesis regarding the potential of the *Hyper-Neurophone* platform to act as a complementary channel for non-verbal interaction when physical co-presence or direct eye contact is restricted. Since the musicians knew the musical piece, cortical resources appeared to be primarily allocated toward mutual adaptation and interaction strategies rather than technical structural tracking.

As summarized in Table II, a macro-level comparison suggests that the system may actively modulate cross-brain connectivity rather than merely introducing unstructured noise. To observe these trends, participants were grouped into two exploratory dyadic configurations: Dyad SU00 (comprising Subject 00 and a designated reference musician, denoted as Ref) and Dyad SU01 (comprising Subject 01 interacting with the same baseline reference musician, Ref). Keeping the reference musician constant across both dyads establishes a controlled neurophysiological anchor to isolate the potential interactive variances of Subjects 00 and 01. Two distinct interactive tendencies were observed under the mediated condition (se02):

- 1) **Potential Global Phase Alignment:** For Dyad SU00, the transition from direct eye contact (se01) to the visual feedback screen (se02) was accompanied by a generalized, statistically significant positive coupling across Delta ($R = +0.0579$), Theta ($R = +0.0441$), Alpha ($R = +0.0367$), and Beta ($R = +0.0330$) bands ($p < 0.01$). This trend suggests that the particle-based convergence visual metaphor might foster shared joint attention and cross-brain alignment in virtual environments.
- 2) **Indications of Complementary Leader-Follower Dynamics:** Conversely, Dyad SU01 appeared to adapt to the visual mirror by establishing a highly significant negative correlation, prominently in the Theta ($R = -0.0984$) and Beta ($R = -0.0522$) bands ($p < 0.01$). This anti-correlation may point toward interactive musical dialogues, where players potentially divide cognitive roles (action/proposal vs. active listening/reception) to maintain coherence when direct gaze is unavailable.

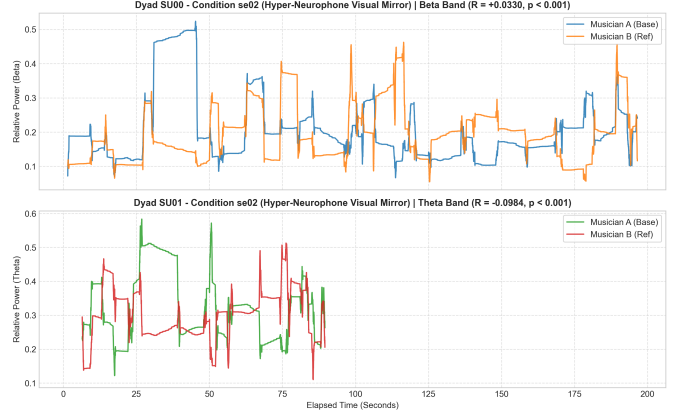


Fig. 5. Continuous elapsed time series analysis for Dyad SU00 (Beta band) and Dyad SU01 (Theta band) under the condition mediated by the *Hyper-Neurophone* visual mirror (se02). Solid lines indicate the rolling mean (~ 1 second window).

These dynamic fluctuations are visually captured in Fig. 5, which plots the smoothed elapsed time series for both behaviors under the se02 condition.

Although the absolute values of R remain in ranges typical for continuous, high-resolution hyperscanning studies ($|R| < 0.1$), the robust significance ($p < 0.01$) provides early evidence that the visual mirror could help bridge the gap in disembodied remote musical collaboration, possibly driving distinct but structurally sound neurophysiological coping mechanisms.

V. CONCLUSIONS AND FUTURE WORK

This preliminary investigation demonstrates the feasibility of the *Hyper-Neurophone* platform as a distributed IoMusT framework for collaborative musical performance. By integrating wearable EEG acquisition, distributed neural processing, and interactive visualization, the proposed architecture enables shared neural representations to serve as an additional channel for non-verbal interaction when conventional visual communication is limited.

The exploratory experimental results provide initial evidence that the visual representation of relative Beta-band activity may promote different interaction strategies during collaborative performance. While one dyad exhibited trends consistent with increased cross-brain synchronization, the other demonstrated complementary interaction dynamics, suggesting that neural visualization may support multiple forms of collaborative adaptation rather than a single synchronization

pattern. Although these findings remain preliminary, they support the hypothesis that shared neural representations can influence interpersonal interaction in musically collaborative contexts.

Given the pilot nature of this study, further experiments involving a larger and more diverse participant population are required to validate these observations and establish their statistical generalizability. Future work will investigate the impact of communication latency and packet jitter on distributed EEG transmission, together with alternative neural descriptors and visualization strategies for multimodal interaction. Beyond these technical developments, Hyper-Neurophone provides a foundation for exploring physiological synchronization in geographically distributed musical collaboration, where performers cannot rely on direct eye contact or physical co-presence. Such scenarios offer the opportunity to investigate how shared neural representations may facilitate interpersonal coordination and strengthen evidence of neurophysiological synchronization in remote collaborative environments. Collectively, these efforts will contribute to the evolution of Hyper-Neurophone as a scalable IoMusT platform while advancing the study of distributed human-human interaction and collaborative musical performance.

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