BCHJam: a Brain-Computer Music Interface for Live Music Performance in Shared Mixed Reality Environments

Michele Romani
Dept. of Information Engineering and Computer Science
University of Trento
Trento, Italy
michele.romani@unitn.it

Gregorio Andrea Giudici
Dept. of Information Engineering and Computer Science
University of Trento
Trento, Italy
gregorio.giudici@unitn.it

Domenico Stefani
Dept. of Information Engineering and Computer Science
University of Trento
Trento, Italy
domenico.stefani@unitn.it

Devis Zanoni
Dept. of Information Engineering and Computer Science
University of Trento
Trento, Italy
devis.zanoni@studenti.unitn.it

Alberto Boem
Dept. of Information Engineering and Computer Science
University of Trento
Trento, Italy
alberto.boem@unitn.it

Luca Turchet
Dept. of Information Engineering and Computer Science
University of Trento
Trento, Italy
luca.turchet@unitn.it

Abstract*—To date, the integration of brain-computer interfaces and mixed reality headsets in Internet of Musical Things (IoMusT) performance ecosystems has received remarkably little attention from the research community. To bridge this gap, in this paper, we present BCHJam: an IoMusT-based performance ecosystem composed of performers, audience members, brain-computer interfaces, smart musical instruments, and mixed reality headsets. In BCHJam, one or more musicians are fitted with a brain-computer music interface (BCMI) giving them the possibility to actively or passively control the processing of their instrument's audio. Moreover, the BCMI's signal controls mixed reality visual effects displayed in XR headsets worn by audience members. All the components of BCHJam communicate through a Wi-Fi network via Open Sound Control messages. We refined the system through a series of test performance sessions, resulting in the creation of a signal quality filter that improved the musician's experience, along with a tuning of control parameters. The developed ecosystem was validated by realizing a musical performance. We provide a critical reflection on the achieved results and discuss the lessons learned while developing this first of its kind IoMusT performance ecosystem.

***Index Terms*—Brain-computer interfaces, Mixed Reality, Performance Ecosystem, Internet of Musical Things**

I. Introduction

The recent advances in technologies at the confluence of the Internet of Things and music have led to the emergence of the paradigm of the Internet of Musical Things (IoMusT) [1]. The IoMusT broadly refers to the network of Musical Things, i.e., devices serving a musical purpose, which are equipped with embedded intelligence and wireless or wired connectivity. By enabling interconnections between Musical Things, the IoMusT paradigm facilitates multi-directional musical interactions between their users. This enables radically new performance ecosystems encompassing musical stakeholders and machines [2], [3].

Lately, different researchers have proposed systems and protocols to interconnect heterogeneous musical devices over co-located or remote networks [4]–[10]. Such interconnection capabilities open a new set of possibilities for creating unprecedented interactive performances. However, to date, the potential of IoMusT-based ecosystems for performance in co-located settings is still largely unexplored and only a handful of studies has been conducted on such topic [11]–[14].

The majority of IoMusT ecosystems available today have mostly focused on the use of intelligent and connected musical instruments [15], [16], smart textiles [13], and networked music performance systems [17], [18]. However, despite their potential in the realm of extended reality interactions, hitherto brain-computer interfaces (BCIs) and extended reality (XR) headsets have received remarkably little attention as Musical Things. As a result, the integration of a set of heterogeneous devices such as brain-computer music interfaces (BCMIs), musical instruments, and XR headsets in an IoMusT-based performance ecosystem has been largely overlooked thus far.

This work received support from the MUR PNRR PRIN 2022 grant, prot. no. 2022CZWWKP, funded by Next Generation EU.

Notably, recent products such as Meta Quest 3 and Unicorn Hybrid Black rely solely on wireless communication to interact with other systems, opening to a higher degree of freedom for IoMusT applications.

To bridge this gap, we present *BCHJam*, a BCMI for live music performance in shared mixed reality (MR) environments. We use BCHJam to create a performance ecosystem that involves: *i)* a musician, who plays a musical instrument and controls its audio effects using a BCI; and *ii)* audience members, who wear an MR headset that enriches the physical stage with virtual constructs modulated by the artist's brain itself. The name BCHJam stands for *Brain-to-Computer-to-Human Jam*[1], which highlights the main intended paradigm of interaction: the musician's brainwaves are processed by a computing device and fed to the audience members of a jam in a multi-modal manner (auditory and visual stimuli). All these interactions are mediated by a wireless network leveraging the common Wi-Fi and the Bluetooth standards.

We describe the design of the *BCHJam* system along with the components of the developed IoMusT performance ecosystem, and provide an online repository with the source code of the project[2]. Furthermore, we report comments on a set of preliminary test sessions. Given the high complexity of the resulting IoMusT-based ecosystem and the various technological and human factors involved, the conducted evaluation primarily aims to set the basis for a future in-depth user study.

Fig. 1: The guitarist testing the BCI commands using Unicorn Hybrid Black EEG headset.

[1]Jam is a term commonly used to refer to informal and mostly improvised musical performances.

[2]https://github.com/CIMIL/BCHJam

II. Related work

A. BCMIs

Electroencephalography (EEG) signals have been employed for music composition for almost a century [19], [20]. Over the past twenty years, the research field of Brain-Computer Music Interfaces has emerged and established [21] as an intersection of BCI and music research. BCMIs can be distinguished into systems for *sonification* and *musification* [22]. In *sonification*, brain data is linearly auralized to produce a non-musical and non-speech sound. The first examples of EEG employed for music precisely used forms of sonification [23]. In contrast, in *musification* the EEG signal is mapped to functions that modulate harmony, melody, timbre, or other musical components. In *musification* systems, the user can interact with a musician, duetting by generating music from brain data through the use of a "BCI musical instrument" [24]. In some systems, musician and BCI user may be the same person, such as in [25] where the system assists a musician's improvisation by adding or removing harmonics without compromising the general direction of the performance. Although BCMI systems are typically designed as local standalone applications, there are examples of systems attempting to use EEG in interconnected applications such as networked music performances [26], [27].

BCMI and BCI in general can be further divided into *active* or *passive* systems, as will be detailed in the next section.

B. Passive and Active BCI

Active BCI and BCMI systems grant the user direct control of commands, typically through the stimulation and detection of event-related potential (ERP). Some of the examples of active BCMIs include using the P300 event-related potentials to manipulate the parameters of a synthesizer [28] or an arpeggiator [29], or using the Steady State Visual Evoked Potentials (SSVEP) to control a system for composition or live performance [30], [31].

Passive BCI and BCMI systems are instead based on features that describe macro changes in the user's mental state. Power-band features in the Alpha or Beta frequency bands have been correlated to changes in the relaxation and arousal levels. For example, low alpha activity is associated with high arousal during music listening [32]. In [33], Beta power features have been reported to better predict emotional arousal elicited by visual and auditory stimuli. Genre preference and tempo of the music were also reported to modulate the amplitude of Alpha and Beta waves respectively [34]. However, it is important to note that the literature presents inconsistent findings and discrepancies on the relationship between EEG power band features and mental state changes.

C. BCIs and XR

While the use of BCI in XR has received considerable attention [35], [36], musical applications are scarce, especially regarding the experience of virtual concerts [37]. Additionally, most of the research in this area focuses solely on audience participation [38], [39]. Such systems employed EEG signal from more audience members to generate real-time virtual visuals in accordance to one's emotional state. This was done so to enhance the sense of social presence and connectedness among displaced users.

Despite some attempts to explore the use of EEG for collaborative musical tasks such as drumming [40], the integration of BCI in Musical XR is still in its infancy, especially from the point of view of musicians. Moreover, all of these projects have explored Virtual Reality concerts, or static experiences using wired BCIs. This approach is not suitable for both for musicians and audiences, that requires mobility and lightweight equipment, especially in the context of a multi-user mixed-reality concert.

The approach adopted in this paper combines elements of *passive musification* and *active* control through ERP, focusing on the networked performance, and opening to novel social interactions between musicians and audience, locally or remotely.

III. Performance Ecosystem Description

In the following, we describe the main components of the developed IoMusT ecosystem[3]. A diagram of the ecosystem is illustrated in Fig. 2. On the left, the image shows the musician with their instrument and a BCI. The signal from the musical instrument or MIDI controller is fed to a computer for processing. In turn, the processed audio reaches the audience through loudspeakers.

The BCMI component is built using the g.tec Unicorn Hybrid Black EEG headset, see Fig. 1, and its plugin for Unity[4], connected via Bluetooth to the BCI-Console, which processes the signal and provides a graphical interface for active BCI control. From the raw EEG signals, the BCI-Console extracts both active targets and passive brain waves (see Sec. III-A), which are processed and then streamed to the local network using the Open Sound Control (OSC) protocol[5]. OSC messages relative to active and passive BCI signals are received by the audio processing system, where they can be mapped to several audio effect parameters. Active signals are converted into input and sent asynchronously whenever the user selects a target. Passive signals are computed every second and streamed over the network. OSC messages relative to passive signals are also picked up by a custom application running on the MR headsets worn by audience members. The XR application provides matching visual effects that are overlaid onto the real scene provided by the headsets' pass-through cameras.

The BCMI of *BCHJam* does not pose a limit on the number of audience members, while it supports either one or two musicians. In the former case, both active and passive signals are provided by the same player, while in the latter each player can provide passive signals and only one can actively control the BCMI.

[3]A video of the ecosystem in action is available at https://youtu.be/aIUvgyed3MQ

[4]The plugin is not open-source and the SDK requires a license.

[5]OSC messages are sent using the UDP protocol.

The following sections present respectively the BCI signals of interest, the musical things for musicians, and the musical things for the audience members.

A. *BCI signals*

The BCMI component of BCHJam uses a mix of Active BCI commands and Passive BCI metrics for the users to interact with the musical performance. This component is built on top of the Unity plugin for g.tec Unicorn, that includes a stimulation paradigm, preprocessing and a classification pipeline. For Active BCI commands we refer to flickering buttons, that produce a response in the user's brain upon focusing on one of them. The plugin implements the time-modulated Visually Evoked Potentials (tVEP) paradigm [41], configured so that every target flickers sequentially for 100ms while the others are off, eliciting a strong and fast ERP response. This response is then classified in real-time using Linear Discriminant Analysis (LDA) by choosing the class with the highest probability of being the stimulus. Passive BCI metrics refer to power-band features of EEG signals, specifically the average Alpha and Beta powers among all EEG channels. These power bands were selected due to the associations with arousal and relaxation previously explained. To avoid erroneous claims on the neuroscience aspects of emotions, we did not tie our features to a specific explanation but rather left it open for later analysis. These features are extracted from the processed signal by computing the Fast Fourier Transform (FFT) method and then by applying the Power Spectral Density (PSD) function in the frequency bins of interest, over a time window of 1 second with a sliding window of 0.4 seconds.

B. *Musical Things for musicians*

- **Instrument:** The system is compatible with any MIDI controller or musical instrument whose sound can be captured by a transducer (i.e., magnetic pickup, microphone) and transmitted as an analog signal. BCHJam was tested with an electric guitar and a MIDI keyboard controller.
- **BCI-console:** The console is an application wrapping the BCI component developed in Unity, and displays visual stimulation targets for the user to focus on. Additionally, the application processes the raw brain signals from the electrodes and extracts active commands (i.e., triggered by focusing on graphical stimuli) and passive metrics (i.e., shifts in selected power bands of the EEG signal). The application integrates an OSC sender to communicate the active BCI commands and passive metrics to other *musical things* in the ecosystem.
  Each console instance can be connected to either one or two EEG devices, one for the combination of active and passive input and one for passive input only. This is due to the limited capabilities of consumer Bluetooth antennas to stream multiple continuous signals at the same time. This setup can open to different combinations of brain sources among musicians and audiences.

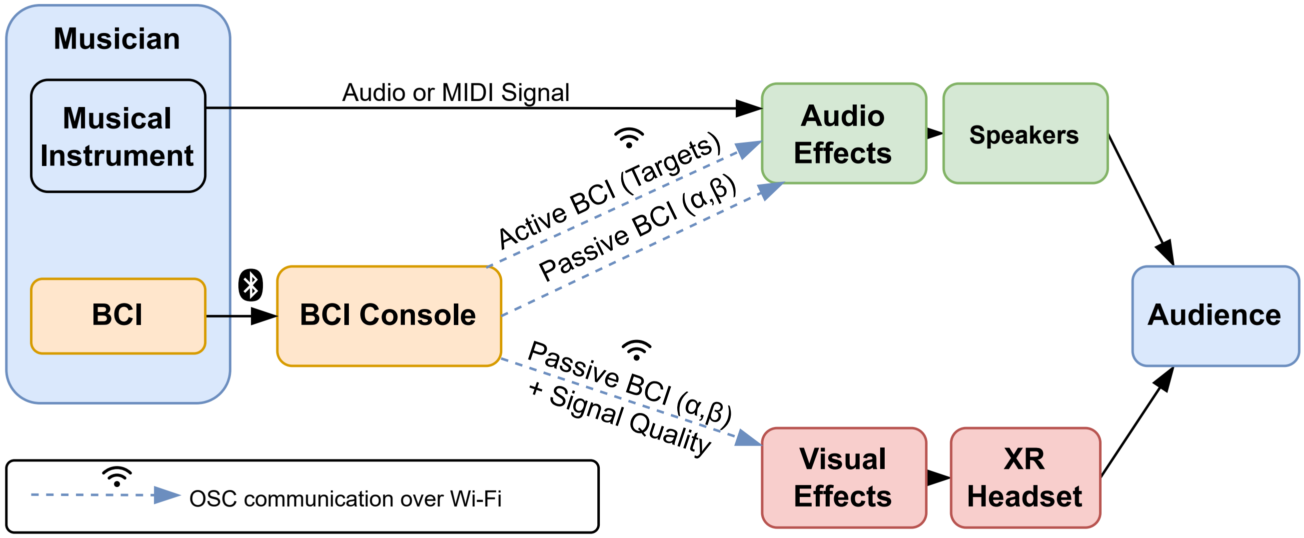

Fig. 2: Diagram of the proposed IoMusT ecosystem. The musician is represented on the left, with both their instrument and their BCI device. The signals from the BCI are streamed via Bluetooth and processed by a computer running the *BCI-console*, where active and passive signal processing is performed. Signals from the active BCI selection of targets are sent via the OSC protocol over Wi-Fi to a Digital Audio Workstation (DAW) running several virtual audio effects. The audio signal from the musician's instrument is also sent to the DAW for processing. Passive BCI signals (alpha and beta waves) are sent to both the DAW and one or more XR headsets, worn by audience members. Finally, the audio reaches the audience member either through acoustic propagation from a set of speakers (in the case of a co-located performance) or through an audio transmission system over the network (for remote performances). Only the co-located modality was tested.

The main components of the console are the visual stimuli targets, which blink sequentially at a constant rate. The blinking pattern varies depending on the number of classes and the defined flash duration. These targets use a high-contrast pattern, specifically an image with a "grain" pattern in which many granules are uniformly scattered. Previous studies showed that a pattern provides better performance than solid colors [42]. Focusing on one of these targets for longer than the focus-time threshold will trigger it. The user is informed of the target selection by a bright-colored outline that appears around it. The target remains in the on-state until the classifier outputs a different class or until the BCI commands are disabled by the signal quality threshold. Four commands were defined, but many others can be added, as long as the limits of the BCI technology are respected. Due to the nature of the ERP stimulation, increasing the number of classes above ≈15 quickly degrades the performance of the system, and the theoretical limit of classes is given by the refresh rate of the screen, locked to 60Hz. Four targets behave in a button-like manner, while the fifth provides a continuous control value through a "power bar" that can be filled gradually with the user's focus. The bar slowly empties when not focused.

Apart from aesthetic elements, only the BCI menu and interface are present on the console. The BCI menu is used to connect the Unicorn headset to the application and start the calibration process. After successful calibration, the application can be started, and all the visual stimuli will start blinking sequentially. The BCI interface lists information about the quality of the connectivity as well as the battery level of the BCI device. Eight squares represent the signal coming from the eight electrodes of the device, where green refers to signal with low impedance, while red indicates a high impedance. Then, there is the classifier icon that states how successful was the training: green for successful, yellow for acceptable, and red for insufficient. A warning shows when there is some data loss during acquisition, resulting in poor performance, and lastly, a small battery icon states the battery level of the wireless BCI headset.

- **Audio Effects:** the client receiving the BCI commands can be any audio processing device or software that supports parameter control through OSC messages. In our implementation, we employed a laptop running a DAW[6], which processes the sound of the musician's instrument through several virtual audio effects (e.g., overdrive, fuzz, chorus, delay, reverb). The DAW hosts an OSC receiver plugin[7]. Incoming OSC messages from the BCI-console (see Sec. III-A) are mapped to the parameters of the audio effects according to the desired sound changes. Button-like active BCI commands were mapped to a drastic change of sound scene (i.e., distorted, clean, and "digital" tones), while passive metrics were mapped to continuous parameters of effects from each scene. Additionally, the actively charged "power bar" provided an additional continuous parameter that was mapped to the intensity of the effects of each scene (e.g., overdrive gain for the distorted scene). The DAW project file is available

[6]The DAW used forBCHJam is Cockos Reaper: https://www.reaper.fm/

[7]For Reaper we used the Realearn plugin: https://www.helgoboss.org/projects/realearn/

online, along with the list of audio plugins used[8]. For the experiments, only publicly available free-of-charge audio plugins were used. The used DAW (Reaper) is not free but offers a free evaluation version with no feature limitations. The choice of effect categories and signal-parameter mappings were agreed upon with the musician who tested the system.

All the components of the musician-side of BCHJam (i.e., BCI-console and Audio Effects) can run either on a single or multiple computers. During the development and testing of the system, we used two computers on a shared Wi-Fi network. Communication of the BCI signals between the console, the computer running the effects, and the *audience things* was handled through the OSC protocol. A screen capture from the DAW project is shown in Figure 3.

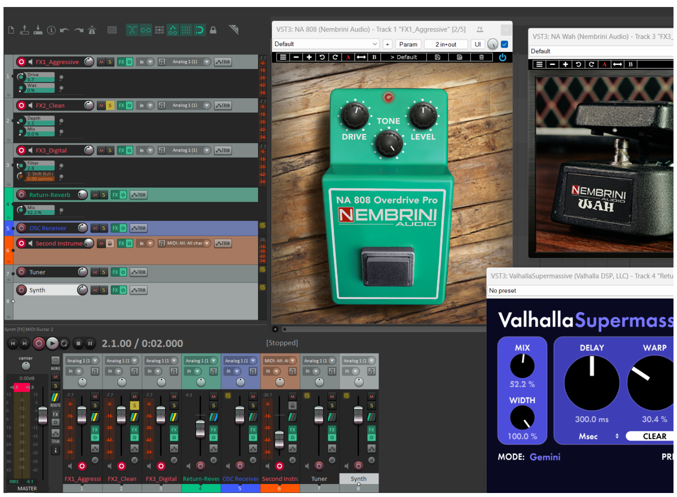

Fig. 3: Screen capture of the DAW, showing a part of the utilized virtual audio effects. Each plugin was selected from cost-free offerings from different developers (e.g., Valhalla DSP, Nembrini Audio). The main three effect scenes were arranged in three tracks. Additional tracks were used for mixing and hosting OSC receivers.

C. *Musical Things for audience members*

- **XR/MR Headset:** BCHJam was developed for a mixed-reality headset (Quest 3 by Meta). The system does not preclude the use of augmented reality (AR) and virtual reality (VR) applications and devices. Therefore, we alternatively refer to MR (for the specific headset) and extended reality (XR) for the application.
- **XR Client application:** Standalone client application developed with Unity 3D. This XR application is developed for Meta Quest 3 and features an OSC receiver. It receives passive metrics used to modulate superimposed different kinds of virtual objects around the physical stage seen via the headset pass-through feature. A 2D capture from the MR headset during performance is presented in Figure 5.

[8]https://github.com/BRomans/BCHJamDaw

IV. Technical Validation

The developed ecosystem and its supported interactions were continuously tested during the development process via several evaluation sessions. Each session lasted about 10 minutes and involved a guitar player and an audience member wearing the MR headset. The initial evaluation sessions were conducted during the development process with the sole musician to refine the BCI-console and tune the parameters of both console and audio effects. As a satisfying level of control was reached, as agreed with the musician, subsequent sessions were conducted with both the musician and the audience.

The goal of the evaluation phase was to technically validate the system in all its components. A more rigorous evaluation investigating the experience of several musicians and audience members was not possible due to the limited number of BCIs and MR headsets available. This aspect is thus left for future work. Hereinafter, we report the comments from a preliminary user study conducted with the musician. This was performed at the end of the development process. No comments from the audience members are reported, as not enough factors were tested during the preliminary study.

Two main parameters of the console were tuned: the z-score confidence threshold and focus-time. The confidence threshold dictates the level of probability that a class needs to reach before triggering the selection of a command. It can be set to 85%, 90%, 95%, or 99%. The focus-time is the time in seconds that the user needs to focus on a single flashing target, i.e., the time that the confidence in that class needs to be above the confidence threshold, to activate the command. The default value is 0, but it can be set to any amount of time. These two values essentially modulate the sensitivity of the BCI and need to be tuned accordingly to prevent false activation, while at the same time allowing the user to select the desired command. A confidence threshold that is too high or a focus-time that is too long can increase the effort required to select a command, while lower values can trigger unintentional entries. For the *Brainpower* command with slider-like behavior, the focus-time was always kept to 0 to allow the user to easily fill up the bar. Parameters can be tuned only from the inspector in the Unity project of the *BCI-console*.

A. *Validation Session 1: Quick Selection*

In the first session with the musician, we used a z-score threshold of 85% and a focus-time threshold of 0.5 seconds. These values were chosen based on previous BCI experiments conducted by the authors. Subsequently, the musician was prompted to freely play with the system while trying to change effect scenes according to the different phrases they intended to play.

At first, after the initial training phase, the musician reported feeling in control, as they were able to quickly trigger effect scenes, as long as they focused and stood rather still. Additionally, they also managed to charge the "power bar" through the fourth target in the console. However, as the session progressed, some effects were wrongly triggered (false

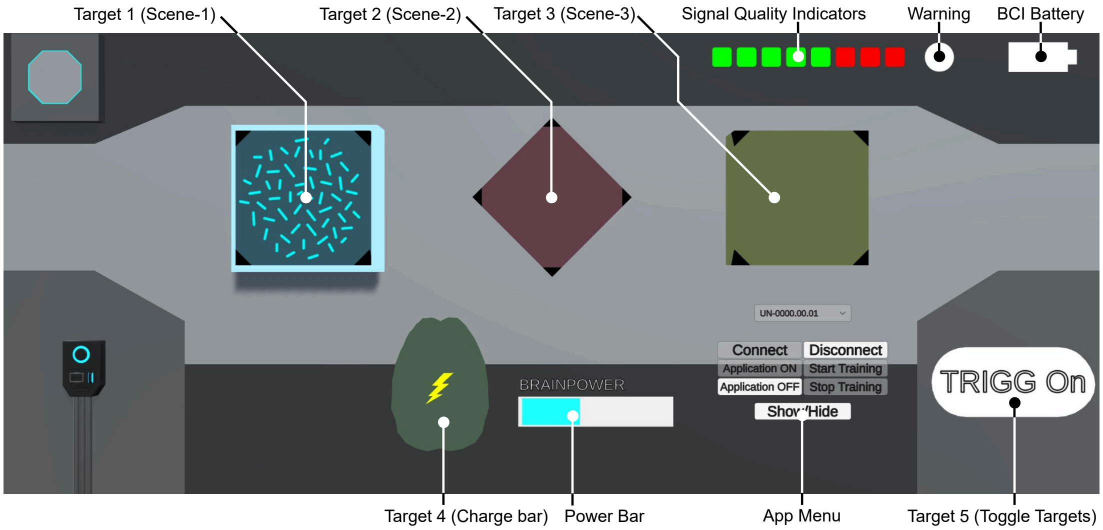

Fig. 4: Graphical interface of the *BCI-console*, as seen from the musician from a computer monitor. The three main geometric shapes in the center of the image represent the main three selectable targets, each changing an audio effect scene (i.e., distorted effects, clean sound, and "digital"/electronic sound respectively). The green brain-shaped target at the centre-bottom charges the bar on the left when the musician focuses on it. The bar level is sent as a continuous value to the DAW and used to control the main parameters for each effect scene. The last target on the bottom right allows the user to turn on or off all the other targets. Finally, in the top-right corner, eight colored squares represent the quality of the signal coming from the respective eight electrodes.

positives). This was made worse when the musician moved inadvertently.

B. *Validation Session 2: Higher thresholds*

Given the false positives encountered in Session-1, activation thresholds were raised slightly. The z-score threshold was increased to 90% and the focus-time was set to 2 seconds. Additionally, a fifth graphical target was added to the Console, which enabled the musician to toggle on and off the other BCI commands to be able to move freely when needed.

During the session, however, even the slight increase in thresholds resulted in the musician struggling to trigger effect scenes. Additionally, whenever the musician managed to successfully change the scene, the high focus-time required made it so that the actual change arrived too late with respect to the musician's intention. The musician reported that this latency made it difficult for them to play freely.

C. *Validation Session 3: Trade-off and Quality filtering*

For the third session, a trade-off between the signal thresholds was found. The z-score and focus-time thresholds were set to 90% and 1 second respectively. The device SDK offers real-time monitoring of the signal impedance on a 2-value scale (0:Bad, 1:Good); in the case of EEG signal a high impedance is most often caused by muscular or movement artifacts. We took advantage of this feature to define a quality threshold below which the BCI is disabled, thus preventing unintended input. We added this mechanism to automatically disable all targets whenever the signal quality of more than 3 channels was 0, indicating potential movement and unreliable BCI signals. This was done to allow the musician to reliably trigger the effects when needed but to also be able to move freely whenever a scene change is not needed. As a result, the musician reported feeling in control of the system, "much more" than with Session-1 and 2. The musician was able to change scenes according to what they were playing (e.g., changing to the distorted effect scene when willing to switch to a more aggressive improvisation). Moreover, they were able to move freely without triggering unintended effects. Lastly, the musician expressively asked the developers to remove the trigger-toggle target on the bottom right of the console, as they felt it was not needed and was more distracting than useful.

D. *Performances*

A first performance with the musician and audience members followed, including the XR-equipped member. Finally, a second performance followed, where the guitarist was accompanied by a keyboard player (see Fig. 5). The keyboard player used a MIDI keyboard that was connected to the same DAW where effects were triggered. In the DAW, different keyboard sounds were assigned to each of the scenes controlled by the guitarist (e.g., acoustic piano, Fender Rhodes electric piano, and Clavinet). In both performances, the guitarist reported feeling in control of the system.

V. Discussion and Conclusions

In this paper, we introduced an IoMusT-based performance ecosystem which incorporates BCI, musical instruments, and MR headsets. The ecosystem is based on the *BCHJam* system, which is made open source and available online. The BCMI was tuned through a series of test sessions with a guitar player to reduce the effort required for active BCI control of musical audio effects and increase the triggering accuracy.

The key findings of our refinement study are that the low control delay required by a playing musician, along with the detrimental effect of natural player movement on the BCI

Fig. 5: Two captures from the XR headset during a session with two musicians. The stripes in the background, the light flares on the left, and the shape of the metaball in the center of the visual field are all virtual elements that were influenced by passive BCI signals. The computer monitor in front of the guitar player was used to display the BCI-console interface for active sound control.

signal, pose an arduous task on active and passive BCMI control. Furthermore, our validation suggests that increasing the focus-time threshold, even if it mitigates false positives, has a detrimental effect on the musician's sense of control due to the delays experienced. Additionally, we found how a successful trade-off between the immediacy of triggering and low false positives can be achieved with a carefully developed filter controlled by BCI signal quality and applied to active and passive controls. This allowed the musician to move freely with no consequences when not needing to control effects.

Finally, we tested the proposed performance ecosystem with a live concert. This showed how modern BCI technologies can be successfully integrated into a distributed system for music performance, thus enabling brain control of the sound of the musical instruments over the network. Equipping members of the audience with an MR headset and/or a BCI device opens various possibilities for augmented interactions with the musicians during performance.

It is worth noticing that the present study has some limitations. The current version of *BCHJam* has only been tested during the development phase and two live performances with two combinations of audience and musicians (i.e., guitarist and pianist). Further improvements and tuning will be required for a more comprehensive user study. Evaluating with more users, including both musicians and the audience, will support the validation of the proposed performance ecosystem. In this preliminary study, the interest was in having the musicians "jam" and get acquainted with the system. Therefore, the collection and analysis of data from user sessions will be addressed in further studies, with the definition of protocols for the musicians to follow. While the system has been tested with two EEG devices connected, there was not any formal experiment with multiple BCI users. Additionally, we intend to expand the networking aspect of the system beyond local networks, leveraging networked music performance systems.

Several additional avenues exist for future work. First, we plan to conduct more investigation with composers, performers, and audience members, to test the different combinations of brain interactions. Multiple instances of the BCI-console and multiple instances of the XR client could be run in parallel, to enable a wider group of musicians and audience members to participate in the performance. This interaction is not limited to physical presence: with the appropriate modifications, some users could join remotely in the musical performance. From the BCI perspective, the choice of features for the passive *musification* can be improved and affective aspects can be accounted for. Additionally, new types of BCI controls can be explored to achieve more complex interactions than switch toggling, similar to what was done with the power bar. From the XR perspective, the modulation of the visual effects will be further explored to understand the relationship between the emotions elicited by the music and the virtual objects. Finally, the system is not limited to human performers: a networked AI agent receiving OSC commands could join the performance using a mix of features coming from both the EEG and the audio, enabling the exploration of new forms of musician-AI interaction in real-time applications.

It is in the authors' interest to keep the system open to use and modification, to foster contributions from the growing communities of IoMusT and BCMI. We hope that the present work can inspire other researchers to explore the integration of BCIs and XR technologies in IoMusT-based performance ecosystems.

The validation sessions were conducted by team members who are proficient with musical instruments, and no sensitive data was collected at this stage. In future studies, we will ensure that the subjects' privacy is fully respected and enforced through anonymization of collected data.

Acknowledgments

We acknowledge the support of the MUR PNRR PRIN 2022 grant, prot. n. 2022CZWWKP, funded by the European Union under NextGenerationEU.

References

[1] L. Turchet, C. Fischione, G. Essl, D. Keller, and M. Barthet, "Internet of Musical Things: Vision and Challenges," *IEEE Access*, vol. 6, pp. 61 994–62 017, 2018.

[2] S. Waters, "Performance ecosystems: Ecological approaches to musical interaction," *EMS: Electroacoustic Music Studies Network*, pp. 1–20, 2007.

[3] R. Masu, M. Bettega, N. N. Correia, T. Romão, and F. Morreale, "ARCAA: a framework to analyse the artefact ecology in computer music performance," in *Proceedings of the 9th International Conference on Digital and Interactive Arts*, 2019, pp. 1–9.

[4] J. Malloch, S. Sinclair, and M. Wanderley, "Libmapper: (a library for connecting things)," in *Extended Abstracts on Human Factors in Computing Systems*. ACM, 2013, pp. 3087–3090.

[5] A. Fraietta, O. Bown, S. Ferguson, S. Gillespie, and L. Bray, "Rapid composition for networked devices: HappyBrackets," *Computer Music Journal*, vol. 43, no. 2, pp. 89–108, 2019.

[6] A. Fraietta, O. Bown, and S. Ferguson, "Transparent communication within multiplicities," in *2020 27th Conference of Open Innovations Association (FRUCT)*. IEEE, 2020, pp. 61–72.

[7] R. Vieira, D. C. Muchaluat-Saade, and F. L. Schiavoni, "Sunflower: An interactive artistic environment based on iomust concepts," in *ACM International Conference on Interactive Media Experiences*, 2022, pp. 245–248.

[8] R. Dannenberg, "O2: A network protocol for music systems," *Wireless Communications and Mobile Computing*, vol. 2019, 2019.

[9] L. Turchet and F. Antoniazzi, "Semantic web of musical things: achieving interoperability in the internet of musical things," *Journal of Web Semantics*, vol. 75, p. 100758, 2023.

[10] B. Matuszewski, "A web-based framework for distributed music system research and creation," *Journal of the Audio Engineering Society*, vol. 68, no. 10, pp. 717–726, 2020.

[11] A. Yaseen and J. Timoney, "Possibilities emerging on the trajectory from iot to iomust: Enabling ubiquitous musical interactions for wellbeing," in *EMPATHY: 3rd International Workshop on Empowering People in Dealing with Internet of Things Ecosystems. Workshop co-located with AVI 2022*, 2022.

[12] K. Mikolajczyk, S. Ferguson, L. Candy, A. Dias Periera dos Santos, and O. Bown, "Space shaping in the design process for creative coding: a case study in media multiplicities," *Digital Creativity*, pp. 1–21, 2024.

[13] F. Visi, T. Basso, B. Greinke, E. Wood, P. Gschwendtner, C. Hope, and S. Östersjö, "Networking concert halls, musicians, and interactive textiles: Interwoven sound spaces," *Digital Creativity*, pp. 1–22, 2024.

[14] L. Turchet, T. West, and M. M. Wanderley, "Touching the audience: musical haptic wearables for augmented and participatory live music performances," *Personal and Ubiquitous Computing*, vol. 25, no. 4, pp. 749–769, 2021.

[15] L. Turchet, "Smart Musical Instruments: vision, design principles, and future directions," *IEEE Access*, vol. 7, pp. 8944–8963, 2019.

[16] L. Turchet, J. Pauwels, C. Fischione, and G. Fazekas, "Cloud-smart musical instrument interactions: Querying a large music collection with a smart guitar," *ACM Transactions on the Internet of Things*, vol. 1, no. 3, pp. 1–29, 2020.

[17] L. Gabrielli and S. Squartini, *Wireless Networked Music Performance*. Springer, 2016.

[18] C. Rottondi, C. Chafe, C. Allocchio, and A. Sarti, "An overview on networked music performance technologies," *IEEE Access*, vol. 4, pp. 8823–8843, 2016.

[19] E. D. Adrian and B. H. Matthews, "The Berger rhythm: potential changes from the occipital lobes in man," *Brain*, vol. 57, no. 4, pp. 355–385, 1934.

[20] D. Rosenboom, "The performing brain," *Computer Music Journal*, vol. 14, no. 1, pp. 48–66, 1990.

[21] E. R. Miranda and J. Castet, *Guide to brain-computer music interfacing*. Springer, 2014.

[22] D. A. H. Williams and E. R. Miranda, "BCI for Music Making: Then, Now, and Next," in *Brain–Computer Interfaces Handbook*. CRC Press, 2018.

[23] A. Lucier, "Music for Solo Performer," 1965.

[24] T. Hamano, T. M. Rutkowski, H. Terasawa, K. Okanoya, and K. Furukawa, "Generating an integrated musical expression with a brain-computer interface." in *NIME*, 2013, pp. 49–54.

[25] B. F. Yuksel, D. Afergan, E. M. Peck, G. Griffin, L. Harrison, N. W. Chen, R. Chang, and R. J. Jacob, "BRAAHMS: a novel adaptive musical interface based on users' cognitive state." in *NIME*, 2015, pp. 136–139.

[26] A. Brouse, "The Interharmonium: an investigation into networked musical applications and brainwaves," Ph.D. dissertation, McGill University, 2001.

[27] C. Levicán, A. Aparicio, V. Belaunde, and R. F. Cádiz, "Insight2OSC: using the brain and the body as a musical instrument with the emotiv insight." in *NIME*, 2017, pp. 287–290.

[28] M. Grierson, "Composing with brainwaves: Minimal trial P300 recognition as an indication of subjective preference for the control of a musical instrument," in *International Conference on Mathematics and Computing*, 2008.

[29] Z. Vamvakousis and R. Ramirez, "P300 harmonies: A brain-computer musical interface," in *ICMC*, 2014.

[30] J. Eaton and E. Miranda, "BCMI systems for musical performance," in *10th International Symposium on Computer Music Multidisciplinary Research (CMMR): Sound, Music and Motion*, 2013, pp. 15–18.

[31] S. Venkatesh, E. R. Miranda, and E. Braund, "SSVEP-based brain-computer interface for music using a low-density EEG system," *Assistive Technology*, vol. 35, no. 5, pp. 378–388, 2023.

[32] C. Mikutta, A. Altorfer, W. Strik, and T. Koenig, "Emotions, arousal, and frontal alpha rhythm asymmetry during Beethoven's 5th symphony," *Brain topography*, vol. 25, pp. 423–430, 2012.

[33] D. O. Bos *et al.*, "EEG-based emotion recognition," *The influence of visual and auditory stimuli*, vol. 56, no. 3, pp. 1–17, 2006.

[34] N. Hurless, A. Mekic, S. Pena, E. Humphries, H. Gentry, and D. Nichols, "Music genre preference and tempo alter alpha and beta waves in human non-musicians," *Impulse*, vol. 22, no. 4, pp. 1–11, 2013.

[35] C. Nwagu, A. AlSlaity, and R. Orji, "EEG-based brain-computer interactions in immersive virtual and augmented reality: A systematic review," *Proc. ACM Hum.-Comput. Interact.*, vol. 7, no. EICS, jun 2023. [Online]. Available: https://doi.org/10.1145/3593226

[36] J. W. Choi, H. Kwon, J. Choi, N. Kaongoen, C. Hwang, M. Kim, B. H. Kim, and S. Jo, "Neural applications using immersive virtual reality: a review on EEG studies," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 31, pp. 1645–1658, 2023.

[37] J. Park, Y. Choi, and K. M. Lee, "Research trends in virtual reality music concert technology: A systematic literature review," *IEEE Transactions on Visualization and Computer Graphics*, vol. 30, no. 5, pp. 2195–2205, 2024.

[38] R. Horie, M. Wada, and E. Watanabe, "Participation in a virtual reality concert via brainwave and heartbeat," in *Advances in Affective and Pleasurable Design: Proceedings of the AHFE 2017 International Conference on Affective and Pleasurable Design, July 17–21, 2017, The Westin Bonaventure Hotel, Los Angeles, California, USA 8*. Springer, 2018, pp. 276–284.

[39] A. Munoz-Gonzalez, S. Kobayashi, and R. Horie, "A multiplayer VR live concert with information exchange through feedback modulated by EEG signals," *IEEE Transactions on Human-Machine Systems*, vol. 52, no. 2, pp. 248–255, 2022.

[40] Y. S. Pai, R. Hajika, K. Gupta, P. Sasikumar, and M. Billinghurst, "NeuralDrum: Perceiving brain synchronicity in XR drumming," in *SIGGRAPH Asia 2020 Technical Communications*, ser. SA '20. New York, NY, USA: Association for Computing Machinery, 2020. [Online]. Available: https://doi.org/10.1145/3410700.3425434

[41] G. Bin, X. Gao, Y. Wang, B. Hong, and S. Gao, "VEP-based brain-computer interfaces: time, frequency, and code modulations [research frontier]," *IEEE Computational Intelligence Magazine*, vol. 4, no. 4, pp. 22–26, 2009.

[42] Á. Fernández-Rodríguez, V. Martínez-Cagigal, E. Santamaría-Vázquez, R. Ron-Angevin, and R. Hornero, "Influence of spatial frequency in visual stimuli for cVEP-based BCIs: evaluation of performance and user experience," *Frontiers in Human Neuroscience*, vol. 17, 2023. [Online]. Available: https://www.frontiersin.org/articles/10.3389/fnhum.2023.1288438