

# THE IMPACT OF AUDIO-VISUAL STIMULATION ON MUSIC IMPROVISATION: AN EEG HYPERSCANNING CASE STUDY

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This case study uses the EEG Hyperscanning method to investigate the impact of an Audio Visual Stimulation (AVS) program designed to induce a creative mental state on the brain activity and music improvisation behavior of one subject pair. Over the course of 2 sessions, 12 repetitions of 2-minute musical improvisation tasks were performed by the subject pair. The 11-minute AVS program called “Creative Pop” precluded the improvisation tasks only in the second session and was presented to each subject using a consumer device called a “Vizr” which generates strobing light patterns choreographed to music. EEG Hyperscanning data synchronized sample-to-sample at a resolution of 500Hz was recorded from 32 electrodes per subject before, during and after AVS stimulation as well as during improvisation tasks. Lempel-Ziv (LZ) complexity and Granger Causality (GC) connectivity were used to measure Brain-Signal Variability (BSV) and Intra/Inter-Brain Synchronization (IBS) respectively. Both BSV and Inter-Brain Synchronization were found to increase during the final minute relative to the full 11-minute duration of the AVS and further increased 30 seconds post-AVS in both subjects. Additionally, an increase in Inter-Brain Synchronization and a decrease in Intra-Brain Synchronization was recorded during the improvisation tasks in the second session post-AVS.

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**Keywords:** Electroencephalography (EEG) Hyperscanning; Audio-Visual Stimulation (AVS); Brain Signal Variability (BSV), Lempel-Ziv (LZ) complexity; Intra/Inter Brain Synchronization (IBS); Granger Causality (GC) connectivity; Music Improvisation.

## INTRODUCTION

### Approach

This project used an EEG Hyperscanning method to study the effects of a strobing AVS program on musical improvisation. Systematic musicology provides an umbrella under which these areas can be connected and approached in a scientific way. Musical improvisation has been an enduring subject of interest not only in the field of systematic musicology, but research using neuroimaging techniques are currently very scarce. This is mainly due to challenges inherent to the technology, and a lack of interdisciplinary collaboration. This case study provided a unique opportunity to take a snapshot of inter-brain dynamics during musical improvisation before and after exposure to stimulation designed to induce a creative mental state. Analysis of the EEG data recorded during this study was performed by JVLMA’s<sup>1</sup> research collaboration partners at the Department of Biophysics, Vilnius University.

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## **Audio Visual Stimulation**

Rhythmic light and sound in the format of AVS programs have long been used by psychologists and neuroscientists to modulate and study brain activity (17–20). The practice of using AVS to induce relaxation or hypnosis saw a rise in interest around seven decades ago (Morse 1993, 111–126), and increasingly since the turn of the century, devices made to deliver light and sound pulses at specific frequencies have been found effective to entrain the EEG into desired states in the context of therapy for pain or anxiety relief (Huang and Charyton 2008, 38–49). Despite being found to be an effective therapeutic tool, findings concerning the specific entrainment frequencies to which the EEG signal responds are inconsistent. Individuals clearly have different and transient responses to AVS (Teplan et al. 2011, 17–24).

Typical AVS programs use strobing lights at specific frequencies paired with music or sound embedded with reinforcing aural pulsations which sometimes modulate in frequency over the program duration. The AVS program used in this case study is not typical – it features a 3x3 grid of LED lights capable of delivering a highly complex and geometric patterns of photic stimulation. This approach to AVS design is aimed not at entraining or modulating to single frequencies, but rather at engaging the visual cortex with constantly evolving patterns. Exposure to this type of AVS is not expected to entrain, but rather entertain – to increase the frequency and level of transience to different states rather than to stabilize a specific state. The creators of the Vizr device propose that this approach may have an impact on BSV, which has been linked to a creative mental state supporting improvisation (Dolan et al., 2018, 18–19).

## **Music Improvisation**

Evidence from EEG hyperscanning studies have found an increase in certain measures of IBS during interpersonal coordination (Chen et al, 2021, 1–2), as well as during music improvisation on the guitar (Müller et al. 2013, 1–2). IBS is predicted to increase during music improvisation, but the relationship between IBS and BSV has not been well explored. This case study aims to investigate the possible impact of AVS on BSV and IBS in the EEG signal, using behavioral data from music improvisation tasks performed by a subject pair to shed light on its effects on co-creative interpersonal coordination.

The coordination of biological or behavioral processes to signals is has been termed interactional synchronization. Signal complexity and intentionality facilitate this synchronization, which facilitates prediction, communication and affiliation (9–11). Synchronization in musical interaction typically requires rhythmic entrainment to a repeating pattern over time, however it does not require that the rhythm contain a constant tempo or time signature. Musical interaction has thus been used as a framework for measuring interactional synchronization (Volpe et al, 2016, 1–8). This enables observing the brain's response to changes in task focus, coordinated behavior

or the environment in a more ecologically valid manner. Indeed, systematic musicologists have called for increased ecological validity, and a more embodied approach in EEG studies (Leman, 2008, 104, Leman and Maes 2014, 236–237) because EEG data alone ‘in a vacuum’ is difficult to relate to processes experienced in everyday life.

The majority of EEG music studies have investigated the listener responses, while relatively few have examined the processes involved in music performance, let alone musical improvisation. This gap is partly due to the EEG signal’s well-documented susceptibility to noise from body movement – an inherent requirement of instrumental performance – as well as environmental interference (Rakotomamonjy et al. 2005, 45–46). In addition, music performance and improvisation are highly complex human behaviors involving multiple variables that make experiments difficult to control (Pousson et al. 2021, 1–2). This case study takes on the technical challenges of recording EEG hyperscanning data from a subject pair during AVS stimulation and music improvisation, and aims to connect findings to others in this relatively new research space.

### **Brain Signal Variability metric**

Lempel-Ziv (LZ) complexity was chosen to measure BSV, in order to connect to and build upon findings in past studies. LZ complexity has been a preferred method for studying brain entropy and signal complexity within a theoretical framework called the “Entropic Brain Hypothesis” (EBH) proposed by the research led by Carhart-Harris (Carhart-Harris et al. 2014, 1–3). The EBH proposes that human cognition may be distinguished by two states: 1) “primary” during which the mind regresses under specific conditions becoming more open to suggestion and emotion, characterized by increased levels of signal complexity, and 2) “secondary” during which more regular and stable cognitive processes and self-awareness are in place, characterized by reduced levels of signal complexity.

LZ complexity is an algorithm initially introduced to measure the complexity of binary sequences (Lempel and Ziv 1976, 75–81), but has been extended to various types of data including the EEG signal for medical and research applications (Radhakrishnan and Gangadhar 1998, 89–94; Zhang et al. 2001, 1424–1433; von Wegner et al. 2023, 296–311). Increased LZ complexity in the EEG signal has been correlated with ego dissolution and vivid imagination (Schartner et al. 2017, 9), both important conditions for the mental state of flow (62–66) that play a role in the creative process of music improvisation (Sawyer 2015, 29–52). In this case study LZ complexity is calculated in the mathematics software MATLAB <sup>2</sup>, based on Lempel and Ziv 1976 (see EEG data analysis pipeline for details).

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<sup>2</sup> [https://www.mathworks.com/matlabcentral/fileexchange/38211-calc\\_lz\\_complexity](https://www.mathworks.com/matlabcentral/fileexchange/38211-calc_lz_complexity)

## **Intra and Inter Brain Synchronization metric**

Granger Causality (GC) connectivity was chosen to measure both Intra and Inter Brain Synchronization, within and between subjects respectively. GC connectivity provides information on the direction of the flow of information, illustrating interactions between brain regions (Tafreshi et al. 2019, 555–566; Zervakis et al. 2011, 302–314; Haufe et al. 2011, 1–2; Kong et al. 2015, 19181–19198).

GC is a statistical test for determining if one time series can be used to predict another, where if a signal *A* causes a signal *B* then past values of *A* should help predict *B*, but past values of *B* alone do not provide sufficient information to predict future values of signal *B* (Granger 1969, 424–438). The use of GC in this case study builds upon previous research concerning Intra-brain Synchronization during expressive music performance (Ghodousi et al. 2022, 1–12). MATLAB was used to calculate both Intra and Inter-Brain Synchronization in subject pairs (see EEG data analysis pipeline for details).

### **MAIN AIMS AND TASKS:**

#### **Main Objectives**

1. Determine and characterize the impact of AVS using the Vizr device on BSV and IBS in context of music improvisation tasks.
2. Evaluate findings and recommend steps for further investigation.

#### **Main Tasks**

1. Identify, record and compare BSV and IBS measures before, during, and after AVS.
2. Identify, record and compare BSV and IBS measures during music improvisation before and after AVS.
3. Record and compare audio during music improvisation before and after AVS.

#### **Expectations**

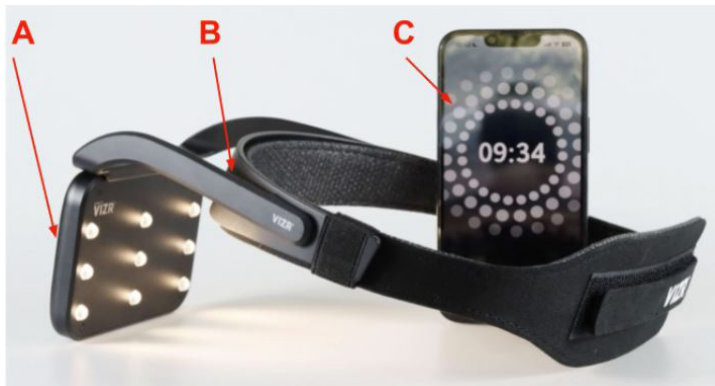
1. BSV measures was expected to be increased post-stimulation, while Intra-Brain Synchronization is expected to decrease.
2. Inter-Brain Synchronization measures was expected to be increased during music improvisation tasks post-stimulation.
3. Audio recorded of the improvisation tasks is behavioral data expected to implicate links between BSV and IBS.

## MATERIALS

### The Vizr device and stimulation program

The Vizr instruction manual and website<sup>3</sup> state that it is a consumer device for adult use, and is not classified as a medical device. Vizr’s creators state that it is designed to provide a sensory experience, entertainment, and to contribute to positive emotional and mental well-being. There are also clear warnings to users regarding epileptic and other types of photosensitive seizures that can be triggered by flickering light, and a light sensitivity test for users who may be unsure.

The device itself (Fig.1) is a plastic rectangular box called a “Light Box”, 115x89x30 mm, weighing 109 grams. On one flat surface is an array of 9 white LED lights arranged in a 3x3 grid. The Light Box snaps magnetically onto a plastic bar mounted on a head strap, positioning the Light Box 8-10 cm directly in front of a user’s eyes. The Light Box connects to a mobile application called “Neurovizr” which controls the Light Box and runs AVS programs via Bluetooth on mobile devices. The Light Box can alternatively be mounted onto stands and positioned at the same distance from a user’s eyes, if other headgear such as EEG electrodes in our case are being used.



**Figure 1:** Image of the Vizr device (A), headgear (B) and Neurovizr mobile application (C).

The AVS programs consist of audio choreographed with strobing light patterns designed to be experienced by users with eyes closed. Within the Neurovizr app there are various categories of stimulation programs aimed to induce mental states for activities such as athletic training, meditation or better sleep. This case study used a stimulation program recommended by the Vizr creators called “Creative Pop”, which aims to boost a creative state of mind. This program consists of 11 minutes of AVS followed by 30 seconds of nature sounds (bird calls and running water) without photic stimulation. The visual component of the program presents a flicker which modulates in frequency from 5-20 Hz, while patterns of movement and intensity within the 3x3 grid change at intervals between 5 to 120 seconds. The audio component of the program consisted of

<sup>3</sup> <https://neurovizr.com/>

instrumental loops (plucked strings, percussion, and a synth pad) made with samples or a synthesizer layered on top of each other. The loops are of different lengths and evolve over the course of the program. There is also the constant presence of a monaural pulse at a frequency of 16-20 Hz synchronized with the photic stimulation.

## **Subjects**

In this pilot study, one male jazz drummer and one female tenor saxophonist – both academic music students with over 5 years playing experience in good physical and mental health – volunteered to participate. They were fully briefed on the study procedure and objectives, and introduced to the Vizr device in person a week before the second recording session to familiarize themselves with its functions and experience of use.

## **METHODS**

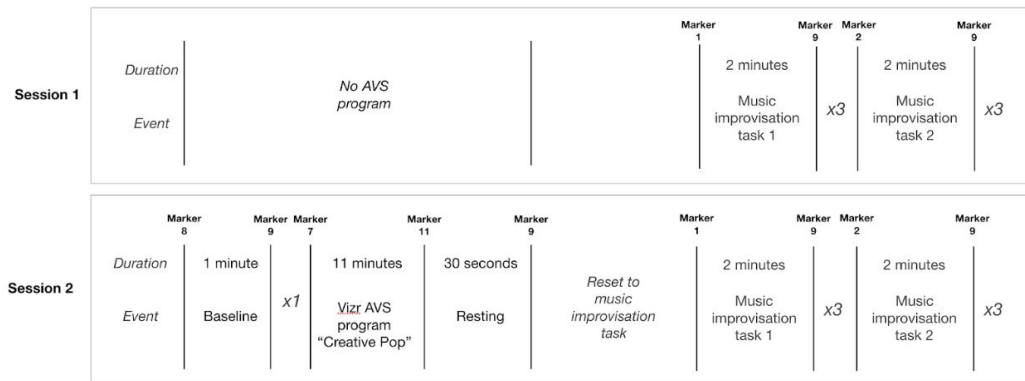
### **EEG and audio signal recording**

The EEG hyperscanning method was used to record 32 channels of EEG data per subject at a resolution of 500Hz using a pair of Enobio 32 NECBOX EEG systems with Dry electrodes and CMS/ DRL grounding provided with an ear clip. EEG data was recorded using two instances of Neuroelectrics Instrument Controller (NIC) software synchronized via the LSL layer. Markers were added to the EEG data manually at the start and end of each trial, thus the hyperscanning data was manually synchronized sample to sample by timestamp. Audio was recorded using a stereo pair of microphones and a Digital Audio Workstation (DAW).

### **Experiment protocol**

One pair of subjects attended two recording sessions taking place on different days. Subject 1 was a drummer, while subject 2 was a saxophonist. A reduced drum kit consisting of a snare drum, floor tom and a ride cymbal were set up next to a chair for the saxophonist in an acoustically treated laboratory space.

Two improvisation task types were performed at each session with different focuses. The first task type was informal – subjects were asked to play as if just for fun, without any pressure to technically impress. The second task type was formal – subjects were instructed to play as if recording for an audition or competition. There was no pre-determined musical material but subjects were allowed to communicate and plan before starting each task. Both tasks had a duration of 2 minutes, and were repeated 3 times each per session, resulting in a total of 12 trials per subject.



**Figure 2:** Recording protocol of session 1 (above) and session 2 (below), where identical music improvisation tasks are performed in both sessions, precluded with AVS stimulation in session 2.

No AVS stimulation was used in the first session. At the second session, subjects were exposed to an AVS program before undertaking the improvisation tasks (Fig.2). Two Vizr devices were synchronized via Bluetooth on one mobile device to play the AVS program “Creative Pop”, and mounted on stands positioned 8–10 cm from the subjects’ faces in darkened lighting conditions. The audio was played at a comfortable level through audio speakers. These adjustments eliminated the need for subjects to wear the Vizr headgear and audio earphones, in order to accommodate for the electrode caps worn on their heads.

## EEG DATA ANALYSIS PIPELINE

This pipeline processes EEG data in several steps to clean and prepare it for further analysis. The steps include:

### 1. Dataset Loading and Preparation:

- EEG data is loaded into EEGLAB from the specified location file (Enobio32.locs).
- The datasets are synchronized based on the first event latencies to ensure temporal alignment across the two datasets (EEG1 and EEG2).

### 2. Synchronization:

- The datasets are adjusted so that their first events start at the same point by removing extra samples and aligning their event latencies.
- If one dataset is longer than the other, it is trimmed to ensure both have the same length.

### 3. Dataset Concatenation:

- EEG1 and EEG2 datasets are concatenated along the channel dimension to create a combined dataset (newEEG), resulting in a dataset with 64 channels.

#### 4. Cleaning and Artifact Removal:

- The combined dataset is cleaned using the `pop_clean_rawdata` function with specified criteria for filtering and noise reduction.
- High-pass filtering is applied to remove slow drifts, and burst artifacts are processed with specific thresholds.

#### 5. Independent Component Analysis (ICA):

- ICA is performed separately on EEG1Cleaned and EEG2Cleaned datasets to identify and remove artifacts (e.g., eye blinks, muscle movements).
- Components are labeled using the ICLabel toolbox, and components with high artifact probability are removed.

#### 6. Segmentation:

- The cleaned datasets (EEG1Cleaned and EEG2Cleaned) are segmented based on specific event pairs (e.g., 8→9, 7→10) and maximum durations.
- For each event pair, valid segments are extracted, stored in a structure (`cut_EEG_struct1` and `cut_EEG_struct2`), and logged for trial counts.

#### 7. Saving Results:

- The segmented data (`cut_EEG_struct1` and `cut_EEG_struct2`) and their corresponding logs are saved in `.mat` files for further analysis.

#### 8. Logging:

- Detailed logs are maintained for each step, including filtering, ICA, artifact rejection, and event-based segmentation. These logs track trial counts and invalid segments.

## EXPLANATION OF THE LZ COMPLEXITY ANALYSIS PIPELINE

This pipeline calculates and visualizes the *Lempel-Ziv (LZ) complexity* of EEG data for specified events and subjects. LZ complexity is a measure of sequence randomness and structural complexity, normalized for each channel and trial.

## PIPELINE DESCRIPTION

### 1. Initialization:

- Parameters like the number of EEG channels (`num_channels = 32`), the events to process, and the subject-specific EEG data structures (`cut_EEG_struct1`, `cut_EEG_struct2`) are initialized.
- An output folder (`D:\VIZR\LZ`) is defined for saving results.
- Channel names are loaded from `StandardChannels.mat` to label the axes in the plots.

## 2. Event and Subject Iteration:

- The pipeline loops through the specified events (Event1\_9, Event2\_9, etc.) and processes data for each subject separately.

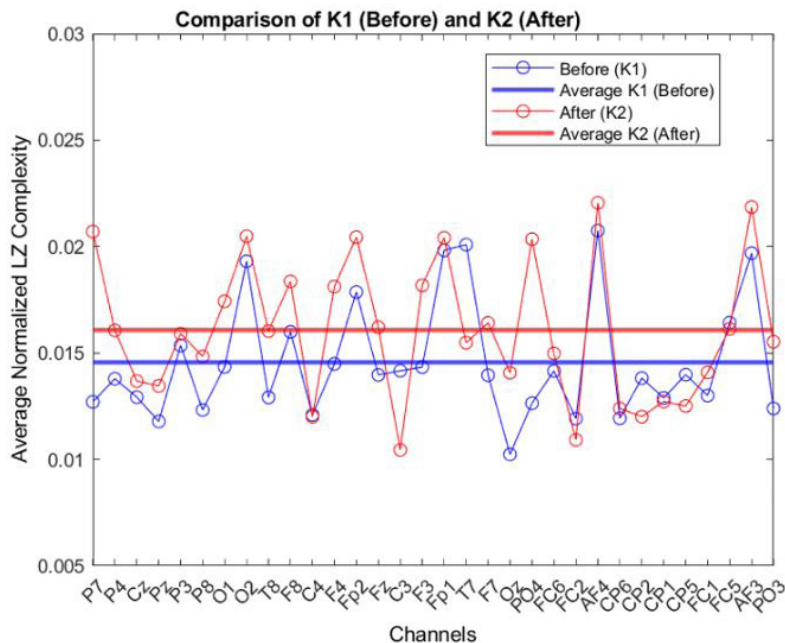
## 3. Trial-wise LZ Complexity Calculation:

- For each trial in the specified event:
  - **Common Average Referencing (CAR):** The mean signal across all channels is subtracted from each channel to reduce noise.
  - **Binary Conversion:** Each channel's data is converted into a binary sequence by z-scoring and thresholding around zero ( $\text{binary\_sequence} = \text{zscored\_data} > 0$ ).
  - **LZ Complexity Calculation:** The binary sequence is analyzed using the `calculateLZComplexity` function to compute normalized LZ complexity for each channel.
- The results are stored in `lz_complexity_per_channel_trial` (a matrix of size `num_channels x num_trials`).

## 4. Channel-Wise and Overall Average:

- **Channel-Wise Average:** The average LZ complexity is computed across trials for each channel (`avg_lz_complexity_channels`).
- **Overall Average:** The mean of all channel-wise averages is calculated (`overall_mean_lz_complexity`).

**In all plotted data, Subject 1 is the drummer and Subject 2 is the saxophonist.**



**Figure 3:** Example of average normalized LZ complexity data plotted per electrode (thin line) and the mean of all electrodes (thick line) during music improvisation tasks before (blue) and after (red) AVS.

## EXPLANATION OF THE GRANGER CAUSALITY ANALYSIS PIPELINE

This pipeline computes *Granger causality* (GC) for EEG data across specified events, focusing on connectivity between two subjects during hyperscanning experiments. The output is an averaged Granger causality matrix for each event, saved for further analysis. Granger causality is a statistical method to determine whether one time series can predict another. In the context of EEG:

- **GC measures directed connectivity:** It indicates whether activity in one EEG channel can predict activity in another.
- **Applications:** Granger causality is widely used in neuroscience to analyze functional connectivity and understand how different brain regions interact.

### PIPELINE DESCRIPTION

#### 1. Initialisation:

- Parameters such as the sampling rate ( $fs = 500$  Hz) and window length (3 seconds) are defined.
- The event pairs to analyse are selected (e.g., Event1\_9, Event2\_9), and the output folder is set to save results.

#### 2. Event and Trial Selection:

- The pipeline checks whether the specified event exists in both subjects' EEG datasets (cut\_EEG\_struct1 and cut\_EEG\_struct2).
- If trials are available, the analysis proceeds.

#### 3. Trial-Wise Analysis:

- For each trial:
  - EEG data from both subjects (32 channels each) is loaded.
  - Common Average Referencing (CAR) is applied to reduce noise.
  - Trials from both subjects are aligned by their shortest length.
  - The trial is divided into **3-second windows** for localized Granger causality analysis.

#### 4. Window-Wise Granger Causality Calculation:

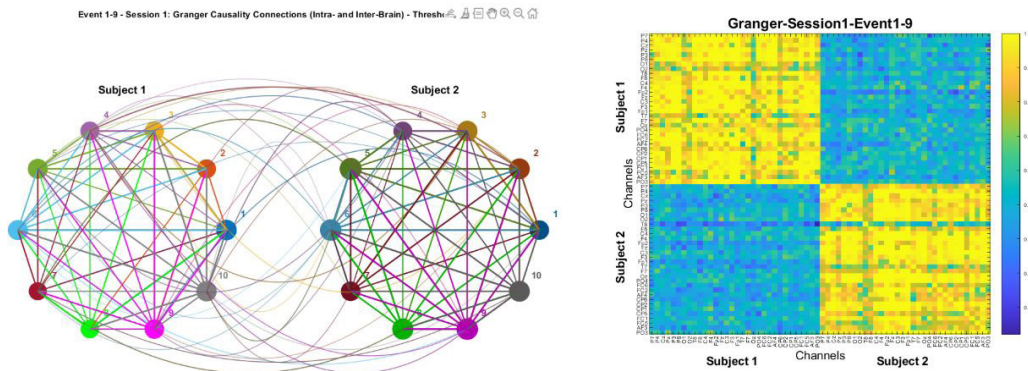
- For each window:
  - EEG data from both subjects is concatenated into a 64-channel dataset.
  - Granger causality is calculated for each pair of channels ( $i, j_i, j_i, j$ ) using a predefined function `granger_cause`.
  - **Significant Causality:** If the Granger causality statistic (FFF) exceeds a critical value ( $cvc\_vcv$ ), the causality is considered significant, and a connection is marked in the connectivity matrix.

## 5. Averaging Across Windows and Trials:

- For each trial:
  - Granger causality matrices are averaged across all windows.
- For each event:
  - The trial-averaged Granger causality matrices are accumulated and averaged across all trials.

## 6. Saving Results:

- The final Granger causality matrix for each event is saved as a .mat file in the specified output folder.
- **Illustration methods: Circular plot and heatmap**



**Figure 4:** Example of circular plot (left) and heatmap (right) for illustrating GC connectivity. In the circular plot Node Radius and line thicknesses are equal to the strength of the outgoing connection. Outgoing connection from each node has the same color of the node. In the heat map Intra-Brain Synchronization are shown within each subject (32 x 32 electrodes) on the top left (subject 1) and bottom right (subject 2), while Inter-Brain Synchronization between subjects is shown on the top right (subject 1 – subject 2) and the bottom left (subject 2 – subject 1).

## DATA ANALYSIS RESULTS

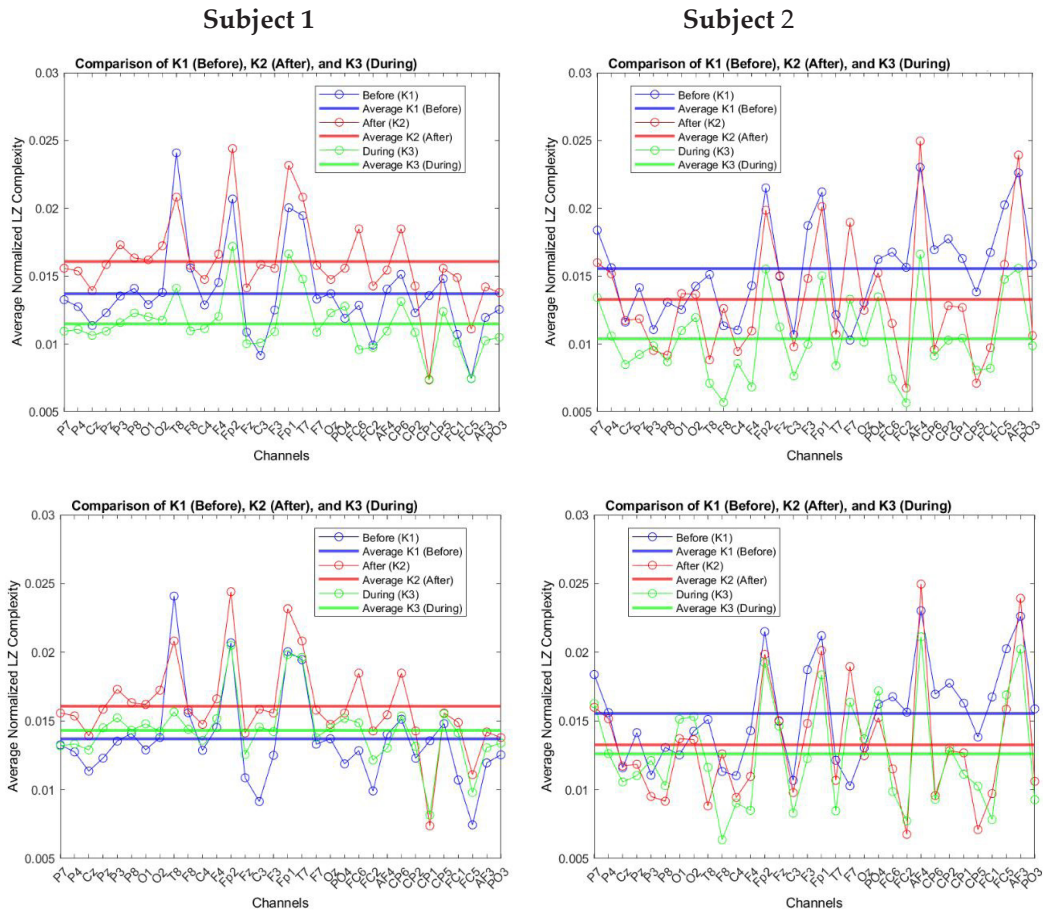
The EEG data analysis was performed with the aim to investigate the impact of AVS using the Vizr device on Brain Signal Variability (BSV) as well as Inter and Intra-brain Synchronization (IBS). Lempel-Ziv (LZ) complexity and Granger Causality were used to calculate BSV and IBS respectively.

### LZ COMPLEXITY RESULTS CONCERNING BSV

The average LZ complexity result was first divided by the duration of each recorded condition, where the AVS program duration was 11 minutes long, the baseline before stimulation was 1 minute, and the resting state after stimulation was 30 seconds.

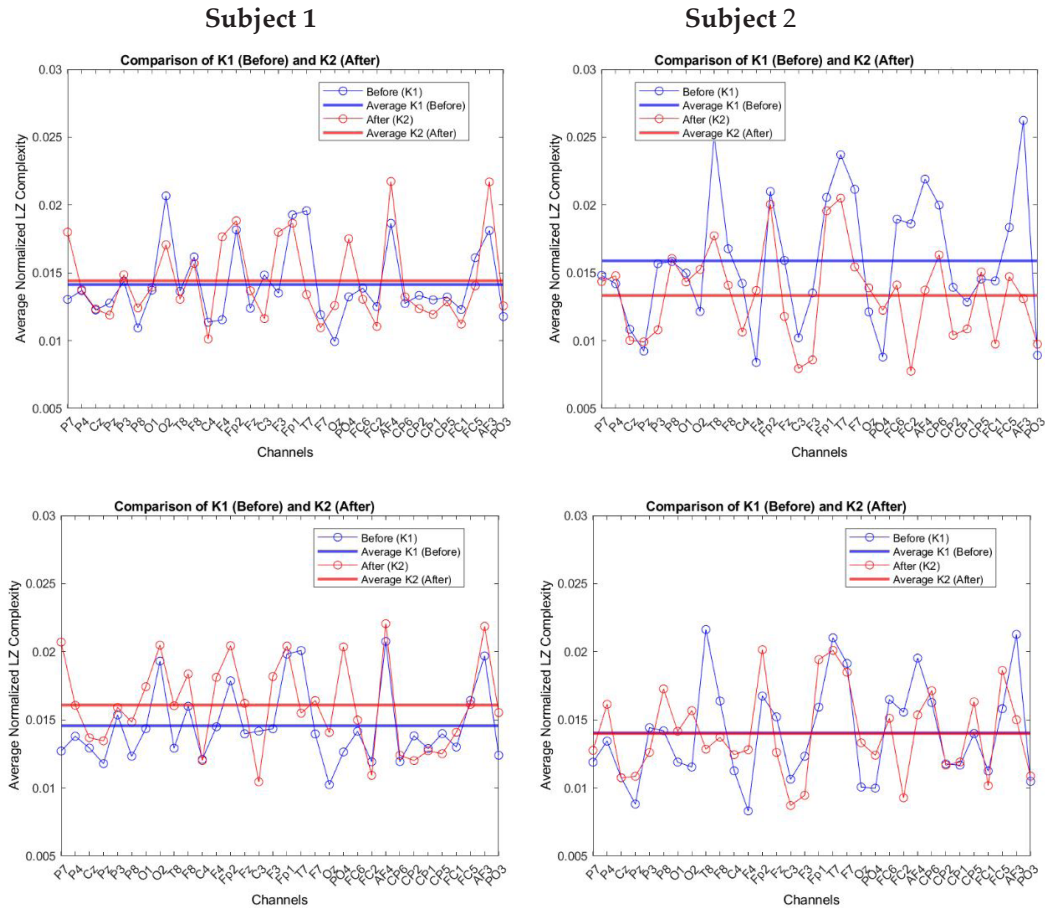
The two upper plots in Figure 5 show average normalized LZ complexity per electrode before (blue), during (green) and after (red) AVS using the Vizr device, in subjects 1 and 2. Average LZ complexity decreased in both subjects during, but also both increased after stimulation. Average LZ complexity after stimulation as compared with before stimulation increased in subject 1 but decreased in subject 2.

The two lower plots in Figure 5 show LZ complexity during only the final minute of AVS, instead of all 11 minutes. It was found that LZ complexity in both subjects was higher towards the end of the stimulation than during the whole 11 minutes, which could imply a steady increase over time.



**Figure 5:** Average, normalized LZ complexity per electrode and across all electrodes, before (blue), during (green) and after (red) AVS using the Vizr device. The two upper plots show LZ complexity during stimulation averaged over 11 minutes, while the two lower plots show LZ complexity during the final minute of stimulation.

Next, LZ complexity was compared during music improvisation tasks 1 (informal) and 2 (formal) between the first session (before AVS) plotted in blue and the second session (after AVS) in Figure 6.

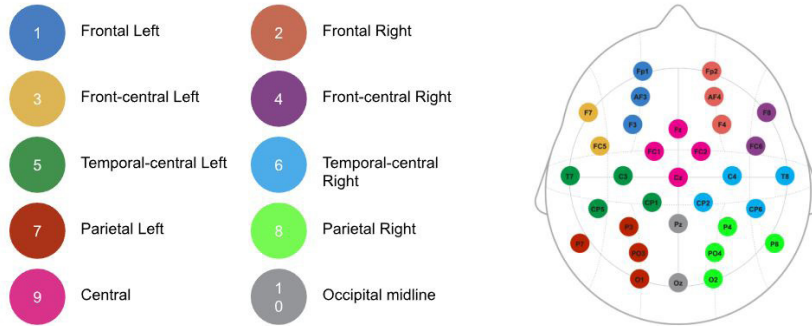


**Figure 6:** Average, normalized LZ complexity per electrode and across all electrodes during improvisation tasks 1 (top row) and 2 (bottom row), before (blue) and after (red) AVS.

During task 1 LZ complexity in subject 1 showed almost no change post AVS, whereas subject 2 showed a decrease, modulating closer to levels recorded in subject 1. During task 2 LZ complexity in subject 1 increased post AVS, whereas subject 2 showed almost no change. The modulation of LZ complexity in response to the AVS program clearly varied between subjects, but some commonalities could be observed. Levels of LZ complexity in both subjects increased in task 2 compared with task 1 post AVS. Odd-numbered electrodes are positioned on the left hemisphere while even-numbered are positioned on the right. LZ complexity in both subjects were more increased in the right hemisphere compared to in the left in both tasks post AVS.

## GRANGER CAUSALITY RESULTS CONCERNING IBS

For clarity of presentation and to connect findings with previous research (Ghodousi et al. 2022, 1–12), data from 32 electrodes was grouped into 10 Regions of Interest (ROI) distributed over the scalp in Figure 7.



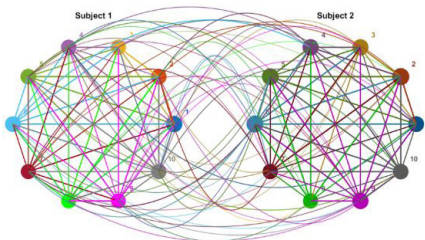
**Figure 7:** 32 electrode montage grouped into 10 Regions of Interest (ROI) for Granger Causality connectivity analysis.

Granger Causality connectivity was calculated before, during and after AVS using the Vizr device (Fig.8). Intra-brain connectivity was plotted as connections within each circle of nodes and remained largely unchanged across conditions. Inter-brain connectivity was plotted as connections between the two circles of nodes, where the most significant changes could be observed.

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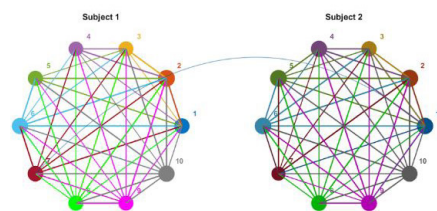
### Pre-stimulation (1 min baseline)

Before Stimulation - Session 2: Granger Causality Connections (Intra- and Inter-Brain) - Thresholded-50



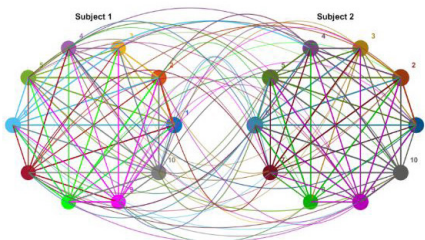
### During stimulation (Full 11 mins)

During Stimulation - Session 2: Granger Causality Connections (Intra- and Inter-Brain) - Thresholded-50



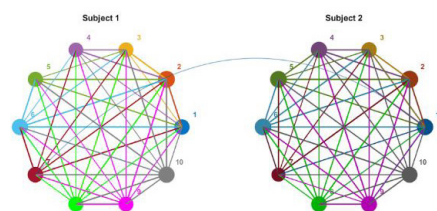
### Post-stimulation (30 sec resting state)

Before Stimulation - Session 2: Granger Causality Connections (Intra- and Inter-Brain) - Thresholded-50



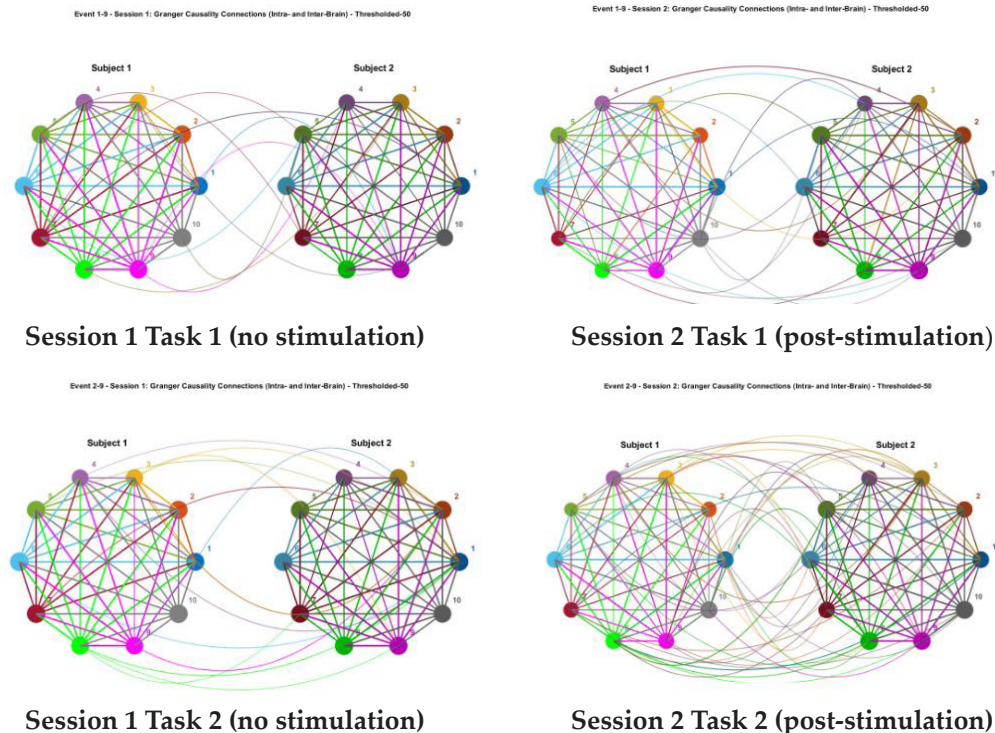
### During stimulation (Final 1 min)

During Stimulation - Session 2: Granger Causality Connections (Intra- and Inter-Brain) - Thresholded-50



**Figure 8:** Intra (within node circles) and Inter (between node circles) brain connectivity before, during and after AVS.

The number and strength of inter-brain connections were significantly increased during the resting state post-stimulation. The final minute of the AVS program also showed more inter-brain connections than during pre-stimulation or during the full 11 minutes of stimulation. Granger Causality connectivity was also compared during improvisation tasks between session 1 (no stimulation), and session 2 (post-stimulation) in Fig. 9.

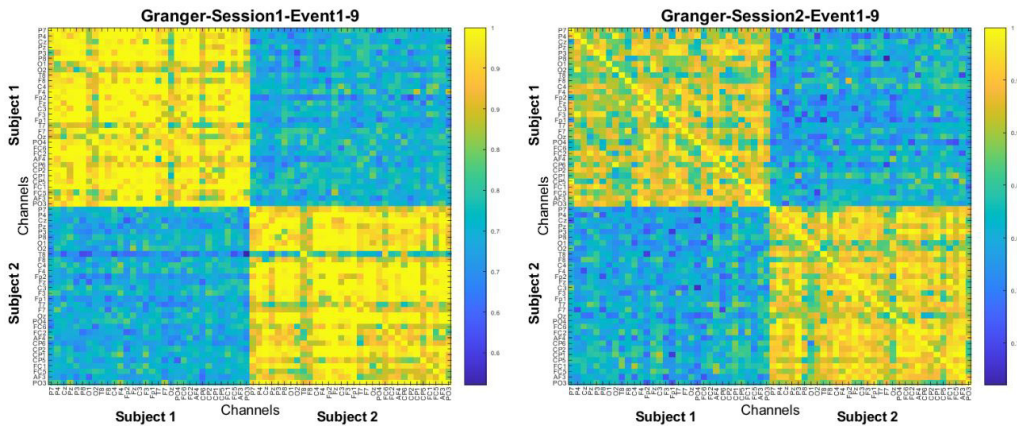


**Figure 9:** Intra (within node circles) and Inter (between node circles) brain connectivity during music improvisation tasks 1 and 2 compared between session 1 with no AVS, and session 2, after AVS.

In both sessions inter-brain connectivity increased during task 2 (formal playing) as compared with task 1 (informal playing). Further, inter-brain connectivity was increased in session 2 (post-stimulation) as compared with session 1 (no stimulation).

Out of all the conditions measured, inter-brain connectivity was found to be the highest during the resting state post-stimulation. This was an unexpected result, since during the resting state, the subjects sat still with eyes closed in the darkened lab, not interacting in any way. Notably, during this 30 second resting period, the Vizr program was playing nature sounds (bird song and running water) designed to ease a user out of the stimulation program.

Another observation was made regarding subject 1. Intra-brain Synchronization was found to be reduced in session 2, post-stimulation during tasks 1 and 2. At the same time, subject 1's LZ complexity was increased, implying an inverse relationship between BSV and Intra-Brain Synchronization (Fig. 10).



**Figure 10:** Intra (top left and bottom right regions) and Inter (bottom left and top right regions) brain connectivity plotted as a heat map electrode by electrode in subjects during task 1 compared between session 1 (left) with no AVS, and session 2 (right), after AVS.

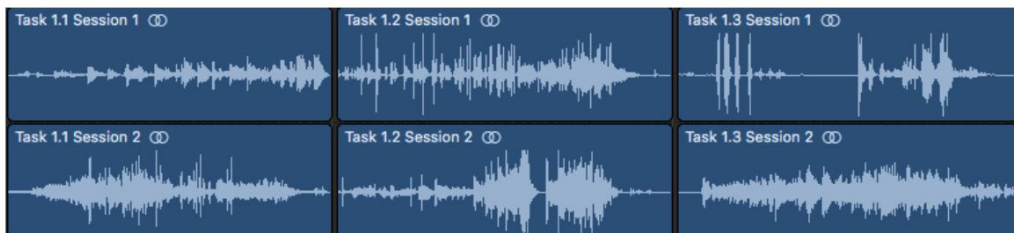
## MUSIC DATA

Alongside EEG data, the audio of the music that the subjects played during the improvisation tasks was recorded. Each of the tasks had a duration of 2 minutes, and were repeated 3 times each. The 2 music improvisation tasks had different goals.

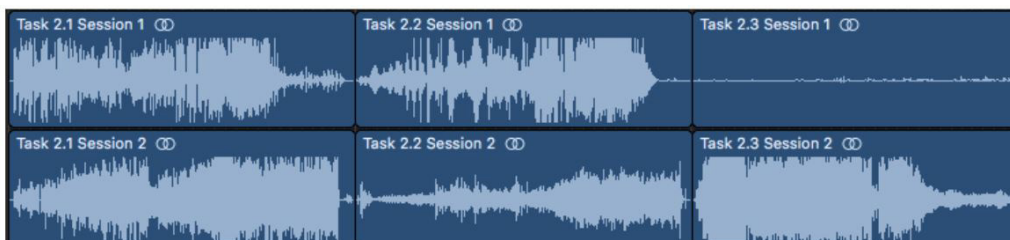
**For task 1**, the subjects were invited to play informally, as if in a familiar rehearsal or studio space. The subjects were already familiar with each other’s playing styles from experience working together in various other academic and jazz projects and recordings, and as such they were comfortable improvising together in this capacity.

**For task 2**, the subjects were instructed to play formally, with aims to impress, as if recording for publishing, or submitting to an audition or competition. The distinction between the two tasks was made in order to observe if BSV or IBS measures may be affected by the goal of the music interaction. Below is an image of the recorded audio waveforms, labeled according to the tasks and sessions (Fig.11).

**Audio signal during task 1 (informal) compared between session 1 (upper waveforms) and session 2 (lower waveforms)**



### Audio signal during task 2 (formal) compared between session 1 (upper waveforms) and session 2 (lower waveforms)



**Figure 11:** Comparison of audio signal waveforms between improvisation tasks 1 (informal) and 2 (formal), and between sessions 1 (no AVS) and 2 (post AVS).

As generally expected, the amplitudes of the waveforms increased from task 1 to task 2, except in the third instance of task 2 in session 1, where the musicians opted to play at a quiet dynamic, which can be more technically challenging and impressive than at a loud or medium dynamic. When comparing session 1 (before AVS) and session 2 (after AVS), there was more overall amplitude in session 2.

When listening to the music itself, it became clear that the rhythms shared by both subjects in session 1 shared a common pulse more than in session 2, where rhythms were treated more like overlapping and contrasting textures. Rhythmic density was generally higher in the second session as compared with the first. Furthermore, the frequency of new ideas introduced in the improvisations was higher in the first session, whereas in the second session, new ideas were more interconnected or overlapped with previously played material.

In session 1 the saxophonist's playing featured more clarity in the role of a solo melodic voice, outlining and accenting on the drummer's ideas. In session 2, the saxophonist's playing featured more rapid runs of repeated notes, looped variations of various ideas, and timbral effects. In session 1, the drummer's playing locked more frequently into grooves, or looped rhythmic ideas, whereas in the second session the drummer's playing featured more ambiguity, gestural accents and textural complexity.

## DISCUSSION

Regarding the findings concerning BSV using the LZ complexity metric, it was found that while LZ complexity decreased during the majority of the duration of the AVS program itself, it was increased during the final minute as well as after stimulation in both subjects. This could imply a steady increase over time. Their average levels of LZ complexity compared to pre-stimulation were different, however a difference in LZ complexity pre-stimulation is to be expected between subjects.

Research (Dolan et al. 2018, 18–19) found that LZ complexity increased in improvisation music tasks as compared with prepared music tasks, and discussed how this increase may potentially facilitate the mental state of flow characterized

by Csikzentmihaly (Csikzentmihaly 1990, 48–67) and how conditions for flow may potentially be linked to increased BSV in primary states characterized by the EBH proposed by Carhart-Harris (Carhart-Harris et al. 2014, 20). In our study, no prepared music condition was involved, however LZ complexity was found to increase in both subjects in task 2 as compared to task 1 post AVS. Recall that in task 2, the subjects were instructed to perform formally - as if for an audition or competition. This finding aligns with conditions for group flow in jazz ensembles where it is less likely to occur in rehearsals when there is no pressure, as opposed to in front of an audience where there is a risk of failure (Sawyer 2015, 43).

Additionally, found the LZ complexity increase localized mainly in the right hemisphere during improvisation music tasks as compared with prepared music tasks (Dolan et al. 2018, 16). A similar trend was found in our results, where LZ complexity in the right hemisphere was increased higher than in the left in both tasks in the second session post AVS, with relatively higher LZ complexity recorded during the second task as compared with the first.

Notably, while subject 1's LZ complexity increased post-stimulation as compared with pre-stimulation, the opposite was observed in subject 2. Consider that subject 1 is a jazz drummer, and the role of the jazz drummer in free improvisation is not necessarily to keep a pulse, but to provide a constantly changing stream of rhythmic ideas while also accenting the rhythms of other players. Consider also then that subject 2 is a saxophonist, and the focus of this role is similar to spoken language – where notes and rhythms become deliberate like words and phrases – but can culminate into arpeggiated runs, timbral effects or textures, and expressive outbursts. Since the saxophonist's role is typically a melodic voice, the more ambiguous and textural rhythms featuring in the drummer's playing in session 2 may have prompted them into less familiar territory. In other words, possibly the drummer was able to let go of the notion of formulating a clear groove more easily, which in turn limited opportunities for the saxophonist to play clear words and phrases, and thus may have demanded a higher cognitive load, triggering a decrease in BSV. Another interpretation could be that the saxophonist's BSV adjusted to the situation presented by the interaction with drummer, decreasing to adapt to the other person's level, in line with evidence that mental states supporting improvisation are communicable (Dolan et al. 2018, 1–3), contributing to a higher sense of shared experience.

Regarding the findings concerning IBS using Granger Causality connectivity, it was found that there were increased Inter-Brain connections during the last minute of AVS, as compared with before stimulation and during the full duration of the stimulation. Subjects were not interacting with each other, but were experiencing the same AVS program sitting side by side in the darkened lab. It is plausible that simply experiencing the same stimuli together with a familiar person, such as in watching an intense movie together, contributed to an increase of IBS over time. The AVS program was long, complex and evolving as opposed to typical stimuli aimed at entraining specific frequencies. This makes it problematic to compare directly with AVS studies

using simpler stimuli at shorter durations with single subjects. For example, a study on the direct effects of long-term exposure to 20 minute AVS programs recorded a steady increase in Intra-Brain Synchronization using coherence measures over 25 sessions. Contrarily, we found a decrease in Intra-Brain Synchronization, but an increase in Inter-Brain Synchronization post AVS using GC connectivity measures. The variables of single subject versus subject pair and simple stimuli versus complex stimuli may be the reason behind these different findings, or it may be that coherence and connectivity measures are not mutually comparable in this respect. Case in point, the team of scholars implemented 6 connectivity metrics programmed into a neurofeedback system for indicating Inter-Brain Synchronization in subject pairs during social interaction, but did not discuss the efficacy or implications of using one metric over another (Chen et al. 2021, 9–10). A more comprehensive comparison of IBS metrics and the implications of their differences is needed to bring clarity to context.

Regarding the unexpected and significant increase in Granger Causality connectivity during the resting state, it is possible that the musical training of the subjects involved, as well as their closeness and familiarity with nature sounds living in Latvia may have been the cause of this surprising result. The melodic and rhythmic patterns of bird calls are particularly ear-catching to people with a highly developed sense of musical perception, and have been explored extensively as musical material, particularly in the composition work of Olivier Messiaen (1908–1992) as well as in the jazz saxophone playing of Charlie Parker (1920–1955). Thus, we may not rule out the possibility these bird calls and the sound of flowing water may have sounded more salient and interesting to the academically trained ear after the long, hypnotic and repetitive audio component of the AVS.

Regarding the findings concerning IBS using Granger Causality connectivity during the improvisation sessions, IBS was observed to increase from task 1 (informal playing) to task 2 (formal playing). This confirmed our expectations that when pressure to impress is added, a higher level of IBS can be observed. A further increase in IBS was observed from both tasks in session 1 (no AVS) to session 2 (after AVS). This confirmed our expectations that IBS may be positively impacted by the AVS program using the Vizr device, however the existing familiarity between the subjects as music colleagues may have been a factor in this result. Additionally, the subjects had been given the Vizr devices to try at home 2 weeks before the second session in order to familiarize themselves with the experience. Their individual experiences may have had priming effects, which may also have been a factor in this result.

## **SUMMARY AND RECOMMENDATIONS**

Photic stimulation using controlled flicker frequencies have been used by psychologists to modulate mental states for decades, and it stands to reason that the AVS programs such as those provided by the Vizr device have a definite impact on the human mind, and in turn may impact performance and creativity. The use of 2 Vizr

devices in parallel to deliver synchronized AVS to a pair of subjects, as well as the use of co-creative music improvisation tasks as a framework of understanding the impact of that stimulation is a unique experimental situation that the EEG Hyperscanning method has potential to shed light upon. In future steps, a precise technical description of the methods used to create the AVS program chosen in this study and the rationale behind its expected facilitation of a creative mental state would be useful for discussing it in comparison with typical AVS designed for EEG research.

This pilot study was limited to data gathered from 2 subjects, playing different instruments with different roles in frames of music improvisation, in 2 different sessions. Prior to the second session, neither of the subjects had prior experience with the Vizv device. Further limitations were that we had no access to the tools and methodology used to design the photic stimulation, nor control over the audio component of the stimulation program, introducing the risk of cultural bias. Increased datasets and better controlled studies are recommended for continuing this research.

Role-specificity is likely to explain why the AVS had some similar and some different effects on the BSV of the two subjects. The only commonality between BSV and IBS findings was that they both increased during the final minute of the AVS program relative to the full duration of the stimulation. No relationship between IBS and BSV measures could be observed during the improvisation tasks themselves, implying that BSV in one or both subjects may have adapted to the situation, but an decrease in Intra-Brain and increase in Inter-Brain Synchronization post-stimulation could clearly be observed. Looking to the future, an increased number of subject pairs is required to be able to apply statistical analysis to the results. Further, more control over the roles of the instrumentalists involved as well as familiarity between subjects is recommended to continue this investigation. Additionally, it is recommended to control and shorten the time allowed to reset to the improvisation tasks in the second session (see Fig. 2), in order to determine whether the increased IBS recorded during the resting state would perpetuate more directly into the improvisation tasks. Finally, it may be useful to perform analysis on the EEG power spectrum which is typically reported and compared to others in the research field.

The investigation of the impact of AVS programs on co-creative processes such as music improvisation has the potential to bridge many fields, inviting them to intersect under the umbrella of Systematic Musicology. Findings from the case study showed: 1) mutual adaptation of BSV, 2) decreased Intra and increased Inter-Brain Synchronization and 3) increased complexity of behavioral data during music improvisation post AVS. This could imply that group-based AVS or group neurofeedback programs may have powerful pro-social effects which may positively influence the quality and outcomes of post-stimulation interactions. These may not be limited to music, but may extend to other types of co-creative tasks requiring goal-directed interpersonal coordination and group flow such as in sport, dance, science, business, or security teams.

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