Stringesthesia: Dynamically Shifting Musical Agency Between Audience and Performer Based on Trust in an Interactive and Improvised Performance

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ABSTRACT

This paper introduces Stringesthesia, an interactive and improvised performance paradigm. Stringesthesia was designed to explore the connection between performer and audience by using real-time neuroimaging technology that gave the audience direct access to the performer's internal mental state and determined the extent of how the audience could participate with the performer throughout the performance. Functional near-infrared spectroscopy (fNIRS) technology was used to assess metabolic activity in a network of brain areas collectively associated with a metric we call "trust". The real-time measurement of the performer's level of trust was visualized behind the performer and used to dynamically restrict or promote audience participation: e.g., as the performer's trust in the audience grew, more participatory stations for selecting the performer's chords were activated. Throughout the paper we discuss prior work that heavily influenced our design, conceptual and methodological issues with using fNIRS technology, and our system architecture. We then describe an employment of this paradigm with a solo guitar player.

Author Keywords

Performance paradigms, Neuroimaging, fNIRS, trust, musical agency, improvisation

CCS Concepts

•**Applied computing** → **Sound and music computing;** *Performing arts;*

1. INTRODUCTION

Trust is a crucial component to promoting performer-audience engagement, as both parties must express some level in confidence to carry out a successful performance. While this interplay of trust has been explored in some interactive musical performances [24, 25], much of the trust literature explores the collaboration of human-agent teams (HATs) [6, 2]. In HAT studies, trust is often evaluated through the manipulation of agent characteristics such as transparency and reliability. In particular, when agents provide unreliable or incomplete information, humans are likely to ignore the information and rely solely on their own experience, resulting in a lack of trust in the agent. Conversely, when agents provide information that is overly reliable, humans may become complacent and over-rely on the agent, resulting in a lack of vigilance and degraded performance [12, 8, 6]. Communication or lack thereof between team members can reveal the level of trust, which can greatly impact the effectiveness of collaboration.

Figure 1: Shows a top-down view of the performance. The trust level of the performer is represented as the size of the orb located behind the performance area.

Similarly, in audience-interactive musical improvisation, trust is built through communication between musicians and audience members, as well as vulnerability and openness to the creative process [5, 21]. However, establishing trust can be a delicate balance, and unreliable (e.g. non-interpretable rhythms) or overly reliable (e.g. static and unchanging rhythms) musical performance can also negatively impact the outcome of the musical collaboration [24, 25].

To explore trust and interactivity in a musical performance setting, some musicians have included the audience in interactive and improvised performance paradigms, where

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the audience contributes music notation or can influence the direction of the music with semiotic information [19, 18, 33, 34, 7, 20, 10, 31]. However, there is a trade-off between how much musical agency, defined as control over the musical content, to give the audience vs. the performing musician/s. Determining musical agency between audience and performer significantly influences the outcome of the musical performance in interactive and collaborative performance paradigms [26, 3, 9].

Bio-sensing techniques have been used to enhance collaboration through transparency in both HAT studies and interactive musical performance. For example, in HAT studies, bio-sensing has been used to display an autonomous driving system's level of certainty, which can inform the driver to take over control before a collision event [17]. In musical performance, bio-sensing has been used to approximate trust and inform performers of an AI-musician's confidence in their musical output [24]. Additionally, bio-sensing techniques have been used to involve the audience in the performance, creating a unique sense of intimacy and engagement between the performer and the audience [7, 27, 5, 21].

One commonly used technique to analyze neural signals and affective state information in performances is electroencephalography (EEG) [7, 21, 27]. However, there is opportunity to contribute literature utilizing optical neuroimaging techniques such as functional near-infrared spectroscopy (fNIRS) in creative settings [35]. fNIRS is particularly well suited for affective state feedback because it provides more spatially resolute information about brain region activation as opposed to EEG, serving to better represent affective states such as trust.

In this paper, we present Stringesthesia, a collaborative musical improvisation between audience and performer that attempts to create an intimacy between the audience and performer that is not as prevalent in traditional performance paradigms. Stringesthesia measures the performer's trust level in real-time using fNIRS, which feeds back to affect the aspects of the performance the audience can control. This feedback is designed to dynamically tune the level of agency the audience or performer have during the performance, such that when trust is high audience members have more agency, and when trust is low the performer has more agency. The authors explain the development, implementation, design process, and performance of Stringesthesia, as well as reflect on how to improve future performances (see Figure 1).

2. RELATED WORKS

The following sections outline prior work that heavily influenced the components of Stringesthesia.

2.1 Measuring Trust

Using fNIRS for the purpose of measuring trust was inspired by numerous studies in HATs [6, 11] and came with several limitations in the context of performance. In this section we describe how fNIRS works, information present in the data stream, and its uses for measuring trust in other fields. In the limitations section we describe the implications of using this technology during a live performance.

2.1.1 fNIRS Data

Functional Near-Infrared Spectroscopy (fNIRS) is a non-invasive and lightweight neuroimaging modality that measures changes in hemoglobin concentration within the brain using infrared light [1] (see Figure 2). It offers several advantages over similar modalities such as EEG and functional magnetic resonance (fMRI). It is non-invasive which enables examination in real-life, naturalistic settings. fNIRS is also more safe and cost-effective compared to fMRI, and has greater spatial resolution than EEG [11].

Following neuronal activation within a region of the brain, oxygenated hemoglobin travels to that brain area. Infrared light is used to detect changes in hemoglobin concentration (oxygenated and deoxygenated), which thus can be used to infer brain activity [22]. fNIRS has been shown to be suitable for measurement during complex cognitive and physical tasks such as yoga [4], dance [28], and classical music performance [30], therefore we used fNIRS during the Stringethesia performance for live neural recording.

Figure 2: fNIRS device being worn. `https://NIRx.net`

2.1.2 Brain Regions Associated with Trust

As fNIRS is a newer neuroimaging technique than comparable technologies like fMRI and EEG, the literature using fNIRS to measure trust and suspicion are limited [11, 6, 2]. However, because fNIRS and fMRI both measure the hemodynamics of the brain, and have been proven to be correlated [22], we can draw the wide swath of literature studying trust using fMRI (as summarized by [11]). The main regions of interest (ROIs) implicated in decision-making and trust include the frontopolar area (FPA), medial prefrontal cortex (MPFC), dorsolateral prefrontal cortex (DLPFC), and the bilateral temporoparietal junction (TPJ) [11, 6] (see Figure 3). The regions have often been implicated in Theory of Mind reasoning, a research paradigm evaluating how one attributes thoughts, intentions and beliefs to others [29]. These areas are often activated during social interactions, evaluation of self and others, decision-making and determining when to trust [29, 23, 6].

Trust was quantified by pilot data collected prior to the performance in which the performer played both cooperatively and competitively with another musician. This data was used to inform the weighting of the brain regions (TPJ, FPA, MPFC, DLPFC) into their respective visual representations in our system architecture. TPJ was given a weight of 2, meaning that these bilateral regions had greater weight in our quantification of trust. FPA was given a weight of 0.5 because FPA is heavily associated with mental workload and has been implicated in less transparent situations [6]. The other ROIs, DLPFC and MPFC, were given a weight of 1 as we hypothesize they plan a similar role in trust.

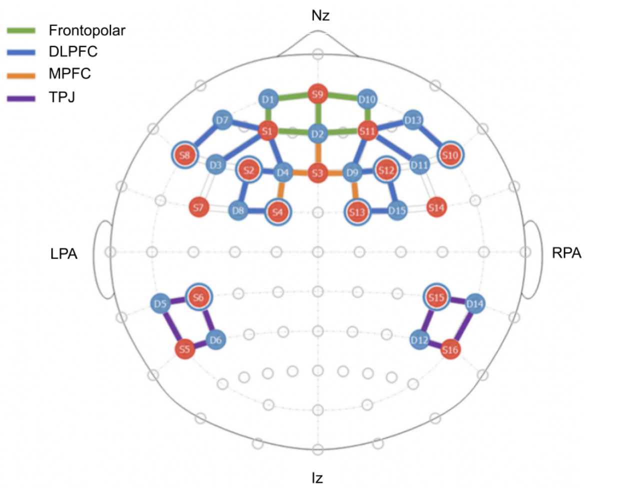

Figure 3: Top-down view of the sensor and detector arrangement for the measurement of trust (S = sensor, D = detector). LPA shows left side of the head, RPA shows right side of the head, Iz represents the back of the head, and Nz represents the frong of the head. Colored lines show brain regions associated with sensor-detector pairs.

2.2 Use of fNIRS in Music Technology

Instruments that adapt to the player based on affective state have been exhibited by Yuksel, to inform music training systems and support creativity [36]. In this project, fNIRS devices were used to measure affective state and adapt the learning or creative environment accordingly. The team proposes a training mode and a creativity mode, whereby separate affective states and brain regions are recorded and act as a proxy to affective state, in this case cognitive workload.

Using mental workload, which produces a reliable signal in the frontopolar area of the brain, creates an easily detectable signal captured by a single optical or electrical sensor [36]. This makes for an easily deployable wearable device for the purpose of detecting the amount of mental workload present in the participant at any given point during the activity.

2.3 Neural Signals in Interactive Musical Performance

Biologically inspired performance paradigms include the use of electroencephalogram (EEG), pulse oximetry measuring heart rate, which were used to guide the tempo and bidirectional communication between audience and performers [7]. The project Ringing Minds, is another example of an installation that explores concepts in multi-musician performance in active and imaginative listening. This promotes the creation of a unique performance whereby collective brain responses of four audience members interact to inform a spontaneously generated musical piece [27].

Another example of musician-audience interaction using EEG is the installation Spukhafte Fernwirkung (Spooky Action at a Distance) [27]. This installation focuses on providing musical ideas for an improvising piano player by way of EEG reading from an audience member. These examples and more inform the way that players, audience members, and installation participants can co-create music using the information provided by the brain of either the performing artist/s or audience members.

An example of a live collaborative improvisation using neurofeedback is Eaton's performance called, *The Space Between Us* [5]. In this performance EEG signals are read from an audience member and a performer. Emotional proxies in the EEG signal are converted into musical phrases played by a computer and a musical score that is presented to a vocalist and piano performer. During the performance both the performing vocalist and the audience member's EEG signals inform the selection of musical passages and seek to illuminate the similarities and differences in their respective emotional states during a live performance.

Stringesthesia draws from these paradigms by using the fNIRS neuroimaging technique to further connect the audience and performer. fNIRS is well suited to accurately measure affective states such as trust, but to the best of our knowledge there are no examples of fNIRS used for musical performance. Our use of fNIRS extends this concept by conveying the internal state of performers' trust to the audience and tuning the musical agency given to the audience based on the performers sense of trust–further connecting the actions of the audience to the outcome of the performance. Because the performer has no rehearsed material the sense of trust between the performer and audience is essential for a positive musical outcome.

3. SYSTEM ARCHITECTURE

In this section we describe the various components of the system and their use in the performance. We then describe how the system architecture supports real-time communication between the audience and performer. We begin the section by describing a high-level connection diagram, then describe the major components including: the performer and trust levels, audience chord selection mechanism, and the reactive visualization system.

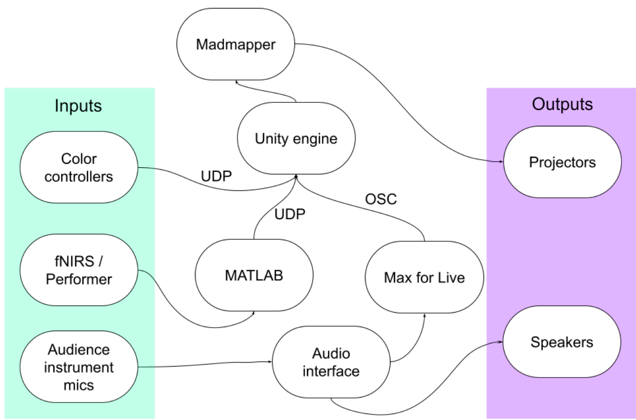

Figure 4: System connectivity diagram demonstrating inputs and outputs

3.1 Live-Stream Pipeline

The components in the Stringesthesia pipeline are configured to live-stream data between the musician, audience members, and a central processor that visualizes the information using projection mapping (see Figure 4). All components are connected via WiFi to a local network transmitting messages using the Universal Datagram Protocol (UDP).

3.2 Measuring and Reporting Trust Levels

Blood-oxygen levels measured by the fNIRS device (NIRSport 2) were live-streamed via Lab Streaming Layer (LSL) to MATLAB. The device had 50 channels spanning across the four aforementioned ROIs (TPJ, FPA, DLPFC, and MPFC). LSL parsed the data stream and calculated the relative oxygenated blood density using the modified Beer-Lambert law equation [16]. It was then sent to MATLAB on a local device which ran further processing on the incoming data stream. For the performance we chose to employ a sliding window average with a window size of 200 data points and subtracted this figure from a baseline calculated at the beginning of each jam session. The average oxygenated blood density levels were produced at a rate of about 0.5-2Hz. Jam sessions were variable in length (2-9 minutes) with a 1-3 minute resting period in between to allow the signal to return to baseline.

3.3 Color/Chord Selection Controllers

Chord selection controllers were provided to the audience to give the audience more agency over the performance. When trust levels were high, more controllers to select chords that the performer had to use in the jam became active for the audience. The color selection controller was made with an ESP8266 microcontroller. It sent a signal (color and device ID) to the audio-visual system using a local network via a User Datagram Protocol (UDP).

In order to bridge the gap in musical knowledge between the audience and the performer, color was used to communicate musical information. We placed 6 controllers in the performance space. Each had six different colors that the audience members could select (see Figure 5, 1, and 8). The performance consisted of 14 different "sets" ranging from 2-9 minutes and had 1-3 minutes in between. Before each set the audience was invited to select a color. Audience members were free to select any color they wished. For the audience member, this may have been an aesthetic choice, an exploration of how the color affects the music, or any other reason the audience member may have had. Selecting a color caused the controller to change its LEDs to match the selection, and sent the selected color to the visualization system which reflected their choice on-screen.

Figure 5: Color/ Chord selection controller (glowing red in image). Figure demonstrates a controller that already has a chosen color. The six buttons show 6 different colors when the controllers are ready to have a color selected. Rhythmic instruments of various kinds are located near the controller stations. Controllers are shown resting on top of music stands.

Six colors were interpreted as chords by the performer who was trained to establish a connection between the colors and chords present in a major key. The colors were presented in a spectral order (red, orange, yellow, green, blue, purple) and represented major scale chords (I, ii, iii, IV, V, vi) respectively to inform the improvisation. Color choices were inspired by common mappings used in color notations between colors and notes in a major scale [15, 14, 13].

3.4 Unity Engine-Controlled Projection

We used five projectors to create the visualizations during the performance. To connect the projectors, we used the hardware video wall controller DataPath (Fx4). After integration of the visual signals into the computer, MadMapper software (v5.1.5) was used to control the precise location of the projection.

The real-time audio-visual system was made using Unity (2021.1.7f1). The visual was made with the unity-driven plugin Visual Effect Graph (VFX Graph). The resulting visuals reacted to the fNIRS and controller signals; both sent via UDP.

3.4.1 Visualization of Trust and Musical Action

The level of trust corresponded to the diameter of the orb behind the performer (when the orb was small trust was low, and when the orb was large trust was high) (see Figure 6). Particles appeared to be flowing to and from the audience members via a stream of diffuse particles and colored lines, connecting the performer to the audience member. The diffuse stream of colored particles converged on the orb creating a multicolored representation of trust. We chose an animation for the orb of particles that appeared to be a complex motion resembling a hive or flocking dynamics. This choice was meant to represent the connection between the audience and the performer as having a life of its own–further drawing the audience toward the shared experience of the collaborative and improvisational nature of the performance.

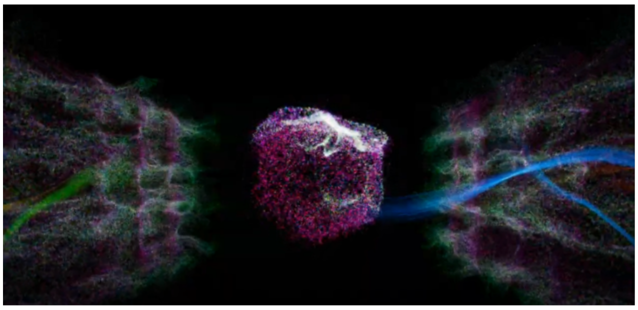

Figure 6: Demonstrates the orb located behind the performer. The larger the orb diameter the higher the trust state

4. PERFORMANCE APPLICATION

The performance took place on the campus of the University of Colorado, Boulder's black box theater. Equipped with six projectors, stage lights, scrum curtains, and a large rectangular floor space (approx. 2700 square feet). The concert lasted for 2 hours and 15 minutes divided by a 15 minute intermission with a total of 115 audience members in attendance.

The timeline of events was constructed so that audience members had a chance to switch instruments, choose colors, and interact in different ways throughout the performance.

Limitations of the fNIRS readings required us to divide the performance into sets, allowing the oxygenated hemoglobin signal from the fNIRS device to return to baseline and enabling a more effective reading of trust (see Figure 7).

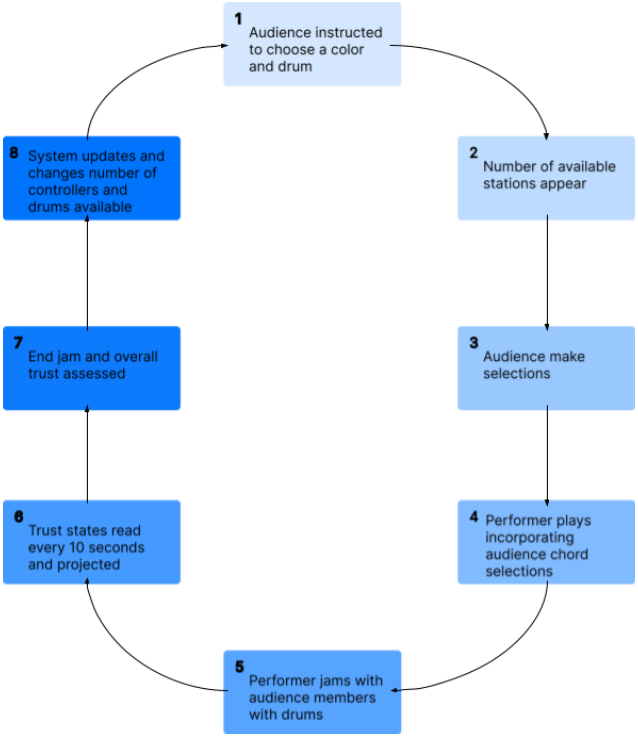

Figure 7: Demonstrates the sequence of events during performance. Cycle is repeated until performance is over. As jam sessions become longer, blood-oxygen levels can saturate. Thus, steps 7 and 8 must account for blood-oxygen levels to normalize (1-3 minutes).

5. LIMITATIONS AND FUTURE WORK

When interpreting fNIRS data it is important to note that hemodynamic signal lags behind neuronal activation. The lag (approx. 3-5 sec [32]) imparted by the technology influenced the performance structure. Both real-time measurements of trust (using a sliding window average) and an overall average of trust at the end of every set were assessed to account for both hemodynamic signal saturation and the signal delay imparted by the technology. EEG has better temporal resolution in this sense, but less spatial specificity offered by fNIRS. A future study could take advantage of the complimentary features of these modalities and use concurrent fNIRS-EEG recording during a performance to measure performer-audience trust.

An additional limitation was imposed by only 6 colors to represent chords in a Western music derived major key. In future performances this can be extended to use a larger range of chords, chord qualities, musical style, as well as color palettes. Additional investigations as to how much influence the audience has over the performance is also of interest to us in the future.

6. CONCLUSION

In this paper we presented Stringesthesia, a performance and underlying pipeline that presents a paradigm for interaction between the audience and a solo musical performer.

Figure 8: Shows a top-down view of the performance facing the crowd.

Inspired by research using trust in human-agent teaming studies, we presented the use of trust in an interactive musical performance using neuroimaging technique, fNIRS. Trust was used to tune the amount of agency either the audience or performer could exert during the performance. During the performance audience members were given a rhythmic instrument and were encouraged to collaborate improvisationally with the performer. When the audience and performer were engaged in cooperative exchange of musical ideas, the visualization of trust visibly changed. When trust levels were high more audience members were able to choose chords that the performer must incorporate into their improvisation and more rhythmic instruments became available for audience members.

This feedback and promotion of trust in both the audience and performer had a very positive impact on the performance based on our observations. We found the visualization of trust using neuroimaging confusing for some, therefore we plan to make the connection between trust and the visualization more clear in future performances. Overall, the performance afforded a unique, engaging, and intimate experience by which both audience and performer collaborated extemporaneously.

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8. ETHICAL STANDARDS

The authors declare that the work presented was conducted in the absence of any conflict of interest (related to either commercial, financial or personal relationships) and in line with the NIME Principles Code of Practice on Ethical Research. An ethic certificate from our respective institutions was not mandatory to conduct our work due to the artistic nature of the project and the absence of scientific procedures involving participants. The first and third author collected data in the form of anonymous, voluntary, written statements.

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