Innermost Echoes: Integrating Real-Time Physiology into Live Music Performances

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Figure 1: *Innermost Echoes* Live Performance at Bar Transit in Hiyoshi, July 2023.

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ABSTRACT

In this paper, we propose a method for utilizing musical artifacts and physiological data as a means for creating a new form of live music experience that is rooted in the physiology of the performers and audience members. By utilizing physiological data (namely Electrodermal Activity (EDA) and Heart Rate Variability (HRV)) and applying this data to musical artifacts including a robotic koto (a traditional 13-string Japanese instrument fitted with solenoids and linear actuators), a Eurorack synthesizer, and Max/MSP software, we aim to develop a new form of semi-improvisational and significantly indeterminate performance practice. It has since evolved into a multi-modal methodology which honors improvisational performance practices and utilizes physiological data which offers both performers and audiences an ever-changing and intimate experience.

In our first exploratory phase, we focused on the development of a means for controlling a bespoke robotic koto in conjunction with a Eurorack synthesizer system and Max/MSP software for controlling the incoming data. We integrated a reliance on physiological data to infuse a more directly human elements into this artifact system. This allows a significant portion of the decision-making to be directly controlled by the incoming physiological data in real-time, thereby affording a sense of performativity within this non-living system. Our aim is to continue the development of this method to strike a novel balance between intentionality and impromptu performative results.

CCS CONCEPTS

• **Computer systems organization → Embedded systems**; *Redundancy*; Robotics; • **Networks** → Network reliability.

KEYWORDS

liveness, sonic art, physiological sensing, music composition, public art, improvisation

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1 INTRODUCTION

Live music performance has been an integral part of music sharing and public connection for many years [10]. Whether it is experienced in a concert hall, a dark basement, a nightclub, or out in the wild, this experience of engaging in and witnessing people exchange ideas and gestures in a musical language is central to the music making experience. Part of what makes this experience so relevant and affective is to see the individuals making this music in real-time [21]. The physicality and the communication between performers and audience members is in many ways inseparable from the experience of making music itself [4]. What happens then if the physicality and physiology of the performers is removed from the body and placed within an external musical artifact? In what ways does this approach change the process of creating, performing, and experiencing live music?

With the proliferation of remote and virtual modes of artistic representation, live music finds itself in an ephemeral state [30]. An important objective in this new dynamic is the conceptualization of an approach that allows these emerging forms of expression not merely to function as substitutes for conventional performances, but to assume an autonomous role within the artistic discourse. The core of this pursuit involves the conception of captivating sonic compositions that leverage physiological sensing and dynamic musical structures capable of responsive adaptation to the real-time physiological data. Musical improvisation, as an inherently spontaneous act [3], is integral to our approach as it affords the flexibility and sense of interpretation necessary to perform alongside such dynamic information as real-time physiological sensing. Although we performers have a loose structure in place, the ways in which we navigate this framework is heavily dependent on the incoming data which steers our performance. The advancement of such an adaptive framework for sonic expression holds the potential to inspire novel experiences, where the intention of the performer and composer gives way to the collective presence of the people involved.

Our proposed method is rooted in the desire to create an adaptive and engaging system in which performers can seamlessly integrate real-time physiological data in a manner which can provide new expressions and communicative gestures in live music. In this paper, we applied our method with the koto, a traditional Japanese stringed instrument. Our method integrates an artifact system which consists of a robotic koto, analog synthesizers, and Max/MSP software to sonify and express impromptu performative dialogues. The reason for developing and utilizing custom musical artifacts was to have an interface that could connect the digital physiological data stream to the human performers, allowing them to interact in a more organic way instead of explicitly instructing the performers on what and how to play. This method is based on empirical studies of data gathered through our initial three performances which were designed to explore different aspects of the integration of physiological data. Through our initial explorations, a solid grounding in musical and performative theories and methods have led us to a multi-modal performative approach.

In this paper we present our setup, methodology and most recent findings alongside the conceptual framework tying this work to several previous projects [12, 29]. At this stage of the exploration we focus on the performer's perspective rather than the audience. Based on several previous works it became evident that focusing mainly on the audience's emotional and physiological responses at the conceptualization and design stages is rather restrictive in terms of the flexibility of artistic expression. With this paper we attempt a different approach to the design of interactive, physiology-aware performances by focusing on the performers first. We discuss and explore the traditional practices for improvisational performances aiming to adapt our methodology to them rather than just providing the artists with a data stream expecting them to design the performance around it.

We further illustrate our conceptual approach with 3 live performances featuring our bio-data acquisition setup, a custom-built robotic koto, a Eurorack synthesizer setup, and Max/MSP software.

The music for these performances was composed for several traditional Japanese and Chinese music players with our custom setup in mind. Moreover, the composer was one of the performers and was participating and supervising every step of this project, thus assuring the musical integrity of this work. The main contribution of this work is the method that utilizes our bio-sensing setup in conjunction with the numerically-controlled musical artifacts and human performers in a performatively organic way. We present the details on the implementation of our systems that have been field-tested in several other projects [12, 29] as well as the evaluation of the proposed method from the performers perspective.

In the next section of this paper we present an overview of the usage of physiological data in musical practices and improvisational music, discuss the different approaches to implementation of such experiences and go over the robotic instruments. In Section 3 we present the conceptual framework that ties the artistic aspects of a performance with scientific interpretation of the physiological data and how these two different fields can co-exist. Details on the implementation of the presented conceptual vision are described in Section 4, where we present the three live shows we organized to test the viability of our approach. Sections 5 and 7 present the results and reflections on the three performances. Here we present the overview of the recorded data, qualitative analysis of the interviews with the performers and our interpretation of the results.

2 RELATED WORK

Novel hardware and software applications have been utilized effectively in the context of musical expression. *Liveness* is a field of research which aims to quantify and debate what makes something "live" from a philosophical and artistic perspective. One such research collective is *Neurolive*, a multidisciplinary group whose aim is "to examine a range of core elements that influence live experiences, acknowledging the multi-faceted and culturally-specific nature of liveness in different contexts" [1].

Since this paper heavily relies on the usage of biodata, we find it to be important to cover how such data was used in other works and experiences. Later on we will discuss how it was used in music. The rest of this section will be focused on musical aspects of this work.

2.1 Physiological Sensing

EEG (electroencephalogram) have seen a variety of applications within musical expression and appreciation. One such application utilized EEG data to play musical works based on the current state of the user [19]. *PsychDome* is another work in which an EEG headset is utilized to induce or encourage a sense of 'form constant' hallucination [34]. In this work, the user's brainwaves are used as an input for adaptive sound and visuals. Another rather novel use of EEG data was presented by Venkatesh et al, in which the EEG headset was used on a person with severe motor impairment [33]. They used to be a violinist, and the use of a bespoke SSVEP-based BCI allowed them to continue to create music despite their impairments.

HRV (heart rate variability) is another useful physiological tool which can be utilized in the context of musical expression. Many studies have shown connections between heartrate variability and music. One example is the work of Iwanaga et al, in which they observed perceived tension and relaxation in users listening to music by composer Erik Satie [16]. Their results showed that sedative music produced a state of high relaxation and low tension. Another similar study by Zhou et al indicated that significant relaxation can occur during music therapy settings [35]. Studies such as these indicate verifiable proof that music can have a direct effect on our physiology and allow listeners to experience bodily affect through these sonic works.

Electrodermal Activity (EDA) was utilized in a dance performance work titled *Boiling Mind*, in which the EDA data of the audience was used to create dynamic changes in the music, projections, and lighting cues in a contemporary dance performance [29]. This project aimed to uses this real-time sensing method to overcome the barrier between the performers and the audience.

2.2 Physiology in Music

Biomusic, or music which utilizes bio-feedback or physiologycal data, came to prominence in the mid 20th century. One of the pioneers of biomusic was David Rosenboom, whose interest in incorporating biological data stemmed from a dissatisfaction with the ways Western music relied so heavily on predetermined compositional practices as opposed to the act of listening or experiencing the music [26]. A precursor and inspiration for this work was the piece titled *Music for Solo Performer* by Alvin Lucier, in which a performer sits motionless on the stage while their alpha brain waves dictate orchestrational aspects of a percussion ensemble [28]. In this approach, the direction of the ensemble is done through a passive means; while the signals are indeed coming directly from the seated performer, there is no reliable way for the performer to knowingly or intentionally controlling this in the same way a conductor would. This was echoed in a recent work titled *Phantom Undulations*, in which the real-time data of a performer was streamed live from Japan to Glasgow and infused with the live data of attendees in the conference through manipulations of the sonic layers [15]. Another more recent example of physiological data in live performances was the *Boiling Mind* project. This work utilized incoming physiological data from the audience during live dance performances, and then applied this real-time data to control and manipulate aspects of the musical score, projections, and lighting cues [29]. In this way, the performers were able to see and hear how the audience was reacting in real-time and adjust their performance along with it.

The use of EMG (electromyography) has also been extensively utilized in live performance works for many years, either by itself or in tandem with other physiological sensing applications. One such example is the project *Biomuse*, which utilized EMG (electromyography), EEG (electroencephalogram), EKG (electrocardiogram), and EOG (electrooculogram) as a means for expressing control over a digital synthesizer via MIDI protocol [22]. Another example of EMG being utilized in live performances can be seen in Pamela Z's work *BodySynth*. With *BodySynth*, Pamela Z developed a method and system of detecting the fine movements of her muscles which were then able to be applied to her live performances as she sees fit [25]. This kind of integrated physiological sensing approach offers a flexibility in application to the performer which is directly tied to their own physicality. With *MappEMG*, the data collected from the EMG sensors captures gestural movements of a performer and then generates vibrotactile feedback. This direct correlation between the physicality and physiology of the performer as it pertains to the ensuing expressive intentions of the performer is central to our research.

2.3 Improvisational Music

Improvisation has been a cornerstone of music performance for centuries and is an integral part of our performance practice and approach with this project. In fact, much of what we would refer to as "early music" relied heavily on the interpretation of the performer. In 1592, theorist Martin Agricola described the distinguishing features between embellishments and ornaments, both of which rely on the improvisation and interpretation of the performers based on a standard and often times vague score [13]. One of the defining characteristics of early improvisation that in many ways persists until today is the establishment of a pre-defined set of rules or limitations [24]. Baroque and renaissance counterpoint employed this method of interpretation regularly through the use of figured bass, which consists of minimal markings which indicate the harmonic movement but leave room for interpretation for the performer [32]. This can be seen in current performance practices such as jazz or contemporary classical music, where a variety of methods of score-based guides are employed. For instance, the technique developed by prolific jazz performer and composer Ornette Comena known as "harmolodics" was an approach based around a freedom from constraints found within more structured music and an added emphasis on individuality within the group [27]. This kind of openness and exploratory approach to live music making helped to usher in the era of "free jazz" and push the boundaries of improvisation and musical expression [17].

2.4 Robotic Musical Instruments

The use of robotic and mechanical control over musical instruments has a long history, with the first player piano being invented in 1897 by Edwin Welte [23]. In recent years, there have been a number of musical applications which have utilized the use of robotics. One such use was in Björk's multimedia project *Biophilia*, which featured several hybrid musical instruments which could be controlled via a laptop using MIDI protocol [9]. This kind of technological interface with acoustic instruments such as a pipe organ, gamelan celeste, and a tesla coil, allowed the performer to engage with and manipulate these instruments in ways which may not have been possible through traditional means. Another example of recent robotic musical intervention is the Machine Orchestra, an ensemble of performers using laptops and several robotic music instruments including a piano, a sitar, a marimba, and multiple percussion instruments [18]. With *Guitar Machine II*, a guitar was outfitted with solenoid plucking mechanisms which can be controlled via MIDI to offer a complex control over the guitar which exceeds traditional means [20]. Through the use of these external objects, certain expressive and musical elements can be achieved that are unique to this kind of setup.

3 CONCEPT

In this work, we present *Innermost Echoes*, a method of improvisational and indeterminate music performance which relies heavily on the real-time physiological data of the performers and audience members. This approach relies on two main hallmarks:

(1) 1. The application of real-time physiological data to rhythmic, melodic, and/or harmonic aspects of the musical structure onto a sonic artifact system.
(2) 2. The response and interpretation of these aspects by the live performers.

This method employs much of the standard practices of live improvisational music (direct communication between the performers, pre-defined limitations and structures) while augmenting this approach with the indeterminate nature of real-time physiological data. Certain results of the data-applied musical elements can be anticipated in advance, but there is enough room for surprises and unforeseen occurrences to shape these live experiences for the performers and the audience alike. The initial inspiration for this method came out of a desire to explore a new kind of musical communication that would honor the tradition of improvised live music while allowing for new forms of musical and expressive language to be developed through a method of real-time data acquisition; something that could not be completely controlled, thereby affording a stronger sense of risk and connection between the people involved. When the performance itself is so innately tied to and dependent on an ever-changing aspect such as physiological data, the works themselves could breathe, modulate, and adapt in a seemingly infinite number of ways, never repeating itself exactly the same.

In order to realize our method, we developed an artifact system which consists of four main elements:

(1) 1. A bespoke robotic koto which is controlled via MIDI protocol.
(2) 2. A control center built in Max/MSP software.
(3) 3. A Eurorack synthesizer system.
(4) 4. A physiological sensing acquisition platform.

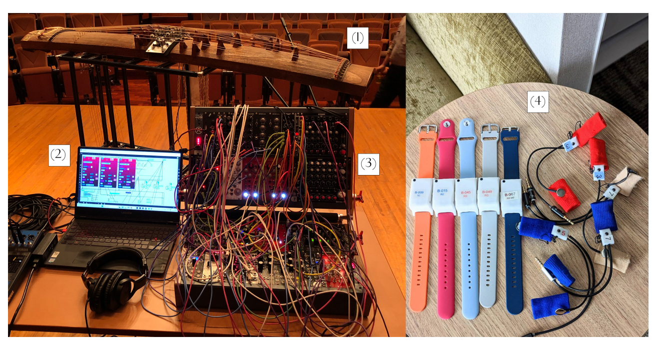

Figure 2: Artifact System (1: robotic koto, 2: Max/MSP software control, 3: Eurorack synthesizer, 4: physiolgoical sensing platform

Through the deployment of these four main artifact elements, we are able to fluidly convey the real-time physiological data and apply it to numerous aspects of the musical works. All of these elements are directly tied to each other via OSC protocol (for communication of the physiological data from our custom-built software) and wired MIDI connections (for the communication of the Max/MSP messages to the robotic koto and Eurorack system).

3.1 Musical Considerations

In developing this method of live performance, certain musical concerns had to be taken into account. The first musical aspect which we focused on was the harmony of the works. In order to begin actualizing this method, we decided to establish certain tonalities for each musical piece ahead of time. By giving ourselves this strong limitation, it allowed a certain degree of musical freedom. Much like the figured bass scores of the Baroque period or a jazz lead sheet, this restriction ensured that all of the performers and artifact system would exist within the same tonal center. In practical terms, this tonality was centered around two closely related keys in order to allow for easy transitions between pieces, thereby removing the need for re-tuning the robot koto mid-performance. While the robotic koto is built to be able to change every string by one half step (the smallest common musical interval in equal temperment), structuring the koto tuning in a way that two closely related keys are easily accessible ensured a more practical and accessible interfacing of the instrument and the performance.

In terms of indeterminacy in the musical works, we focused heavily on the tempo and the note choice in our first iteration. By mapping the overall tempo of the pieces to the average BPM of the performers, we could explore a slightly varying but still somewhat stable speed. This approach was also applied to the note choices for the robotic koto. For instance, in most of the pieces, the koto was given a set of notes with which it could choose and that choice was then dictated by different forms of physiological data. This offered a means of generating familiar and predictable but still somewhat indeterminate performative gestures.

Finally, we mapped some more subtle aspects to the Eurorack synthesizer system. In this system, comprised of many varying modules for sound production, modulation, and manipulation, we followed three distinct mappings: pitch selection, wet/dry effect application, and LFO modulation. For the pitch selection, these oscillators were given a set of pitches which could be chosen and a set of envelope parameters (attack time, decay time, sustain length). The same was applied to the wet/dry effect application (how much of the modulated sound is heard vs the dry unmodulated sound) and the LFO modulation (frequency/speed of the modulation, amount of LFO applied to other modules, and modulation waveform). All of these features were reliant on the performers data and blended with the performative nature of the Eurorack system itself.

3.2 Physiological Sensing and Data Processing Pipeline

In our work, we are processing the real-time physiological data of two groups: audience and performers. This data is then utilized to define certain behaviors in the musical artifacts being used (robotic koto, Max/MSP, and Eurorack synthesizer), thus creating performative aspects which are directly tied to the people experiencing these live performances. In order to provide the real-time physiological data related features to the performers, such as average heart rate (BPM) or information on the audience arousal derived from the EDA and HRV we have used the following setup.

Each audience member was wearing a custom made physiological sensing device with analogue PPG (PhotoPlethysmoGraf) sensor and 2 EDA electrodes on their fingers (See Fig.2 Right). The analog PPG signal was passed through an RC filter and fed to an ADC sampling it at 200 Hz with 12 bit resolution. EDA was measured from the two Ag/AgCl electrodes using a Wheatstone bridge, a hardware filter and a differential 16bit ADC, sampling at 10 Hz. Sampled data was buffered by an ESP32 MCU and sent to the Data Processing Server in 500ms batches with exact current timestamps twice a second. Server software written in Qt C++ was managing the device activity, data recording, processing and streaming. The data from each device was passed to a python script in a separate process for analysis and feature extraction. Python script accumulated only the last two minutes of data for each device and ran the feature extraction every 5 seconds. The resulting HRV and EDA features were updated every 5 seconds. Since the performance required only 2 variables, namely audience BPM and a reflection of the state of audience arousal level, and the extracted features are numerous and are hard to interpret directly, we added an extra step to aggregate them and simplify the data presentation and interpretation.

EDA features related to emotional experiences, namely the phasic peaks, are rather easy to identify and relate to the subject's emotional experience and arousal levels[5, 7, 14]. In this work we chose to use the number of phasic peaks per minute, as it was very fitting for our processing pipeline and is often used for arousal estimation. Another metric we focused on is HRV metric RMSSD (Root Mean Square of Successive Differences between consecutive heart beats)[2, 6, 31]. Simply speaking, an increase of RMSSD is associated with parasympathetic nervous system activation, which steers the body to so-called "rest-and-digest" mode. This implies that the subjects are likely to be excited, aroused, and active when RMSSD suddenly decreases.

Since we cannot realistically establish any baseline excitement or arousal levels in the current settings, we focus on the changes of these parameters signifying increase or decrease in arousal/excitement or a shift in the sympathovagal balance (balance between parasympathetic and sympathetic nervous systems activity). Mathematically it is expressed as the ratio of the previous parameter value and the difference between the previous value and the new value. It can be expressed as RMSSD_USED = NEW_RMSSD / PREVIOUS_RMSSD - 1; where the variable that we use for the performance is RMSSD_USED, NEW_RMSSD is the result of the latest feature extraction and PREVIOUS_RMSSD is the previous value. Identical calculations were performed on the EDA Phasic peaks-per-minute parameter.

Considering that ideally for this performance we should utilize only one parameter, instead of choosing from all the available metrics, we decided to combine the momentary changes in the number of EDA peaks per minute and the changes in the RMSSD into one variable. In order to combine the two derived metrics into one we used a simple average of the two.

Since it is highly unlikely that the selected features will instantly change by a lot, and each increase will eventually be countered by a decrease and vice versa, such a ratio-based approach allows us to expect the values to be within -1..1 range and be near-normally distributed around zero. While numbers can theoretically fall outside of the -1..1 range, we limit the range to -1..1, as any numbers outside this range most likely are caused by noise. Such extremes were prevented from passing through to the musical artifacts in the Max/MSP software.

Such calculations were done for every audience member every 5 seconds, then the results were averaged for the whole audience and sent via OSC to the artifact system.

4 LIVE PERFORMANCES

In order to begin evaluating our method in a manner which is on one hand scientific and reproducible, and aligned with traditional performance practices on the other, we presented three live performances on two dates in Hiyoshi, which is located in the city of Yokohama, Japan. These live performances were meant to explore our method in a more visceral and direct way as opposed to our previous tests in a lab setting.

4.1 Setup

4.1.1 Performance Practice. Instead of more structured rehearsals, we focused on conversations surrounding the concept and intention of the works. Key signatures, vague structural forms, and keywords for different moods were established in advance. For each performance, the instrumentation was established in advance. All of the performers were experienced in improvisational music and had varying backgrounds (traditional Japanese, jazz, Western classical, and experimental musics). This broad background afforded us the opportunity to blend various styles of music and approaches to improvisational expression, thus creating works which were not defined by one genre or tradition but instead rooted in experimentation and fluid sonic characteristics.

The approach in which the physiological data was implemented into the musical artifacts was developed in a similar manner to a commonly held rehearsal approach found in free improvisational ensembles, in which the performers rehearse within the specific sonic setting which will be possible in the performance [8]. Since these performances would always be utilizing these musical artifacts, we spent an extensive amount of time improvising alongside the robotic koto and Eurorack synthesizer while trying numerous methods of implementation until the suitable implementation was determined. The data was collected via our physiological sensing wristbands, processed by the sensing software, sent to Max/MSP via OSC, and then routed to the robotic koto and Eurorack synthesizer via MIDI. The implementation and routing of the physiological data was adjusted and reassigned until the desired outcome was achieved.

4.1.2 Software. The main control center for this artifact system was designed in Max/MSP software (shown at Figure 2(2)). This consists of four main sections:

(1) 1. A UDP receive port which takes in all of the physiological data from the network.
(2) 2. A series of "zmap" objects which scale the data into more efficient ranges and formats, depending on the intended application of the data.
(3) 3. A MIDI section which is dedicated to the control of the robot koto, running on Channel 1.
(4) 4. A second MIDI section which is dedicated to the Eurorack system, running on Channels 2-16.

The applications of the Max/MSP software varies rather greatly, and in most cases depends on the song structure and intention. Generally speaking, the application of data falls under the categories of triggers and floating point data. For the trigger category, this is generally used to dictate which koto notes are performed and for the triggering of Eurorack oscillators and envelopes. Much of this trigger data is reliant on the average BPM data of the performers. With floating point data, this is generally applied to the pitch range, sustain length, envelope release time, LFO release time, and the structure of the song itself. When determining the length of the song from floating point data, we use a range of 0.-1., and then set limits to attempt to give some form of predictability while still offering a certain degree of unknown.

4.1.3 Hardware. The koto is a Japanese string instrument inspired by the Chinese guzheng in the 7th and 8th century. A standard koto is typically a 182 cm long and 30 cm wide Paulownia wood body, with movable bridges and 13 strings. The length, wideness and height of a koto is suitable for the needed hardware to be built in as well as the adjustable space between the strings and the wood surface created by the bridges (see at Figure3). Our robotic koto was built using an old used 13-string koto which has 13 solenoids and 13 linear actuators affixed to it (shown at Figure 2(1)). These operate by the solenoids striking the strings and the linear actuators pulling the strings down from the bottom, thereby raising the pitch by approximately 1 half step. This is limiting in comparison to a human koto performer, who can precisely bend the strings in a wide range of distances, from microtonal steps to as much as a perfect fourth or more. However, this approach was the most efficient and practical solution we could develop for this first design iteration. The robotic mechanisms are all controlled by a custom-built motherboard which also maintains the MIDI communication protocol.

The Eurorack system consists of roughly 50 different Eurorack synthesizer modules, with a wide range of capabilities (shown at Figure 2(3)). These were organized into several groups, including sound generators, envelopes, LFOs, effectors, and utilities. The main targets for the physiological data were the sound generators, envelopes, and effectors, while the LFOs and utilities were only occasionally used with the data. The choice to go with physical synthesizers as opposed to digitally generated synthesizers within Max/MSP was mostly an artistic and aesthetic choice. Since we are using physiological data as a means of expressing our physical bodies, we chose physical synthesizers to thereby express this data in a more direct manner. Simply speaking, we felt more artistically free and confident with using physical sound generators as opposed to digitally produced sounds.

4.1.4 Sensing Setup. For all three performances we used identical sensing setup as described in the previous section. The only difference was that in the first two performances the aggregated arousal/excitement related data was not used. It was used in the third performance only. In all three performances, investigators

Figure 3: The Hardware of the Robot koto

helped to put on the devices to assure the correct placement of the PPG sensors and EDA electrodes. All the data recording and the analysis were done in real-time on-site. We used a separate WiFi network for the sensing devices connectivity.

4.2 First and Second Performances

In our first public performances at Keio University Media Studio in Hiyoshi, we presented two shows lasting roughly 35 minutes each. These performances were given on May 19th to around 40 audience members. In this performance, there was one performer on Eurorack synthesizer/baritone guitar and two koto players. In addition to our three performers, we also had the robotic koto at the center of the performance space. The performance consisted of five songs, of which all utilized the physiological data in some way.

(1) 1. *Interlude*: Featuring performers average BPMs triggering atonal sounds from six different analog VCOs and the robotic koto. During this piece, the performers stood still.
(2) 2. *Ringing*: Featuring repetitive robotic koto arpeggios with tempos tied to the performers average BPM.
(3) 3. *Traditional Improvisation*: A completely improvised piece which featured the two koto performers using a traditional Japanese style with EDA controlling Eurorack effect parameters. 3D printed koto bridges with piezo pickups detected which strings the performers plucked and then applied that attack data to the robotic koto.
(4) 4. *Chorale*: A meditative piece which used the average BPM of the performers to control the tempo and EDA to control the sustain of the Eurorack reverb unit.
(5) 5. *Lioness*: A song with a predetermined tempo which took changes in the average BPM of the performers to determine the song length and koto activity. This included four possible lengths of repeating gestures and a set of four possible levels of activity ranging from nearly silent to extremely active.

The robotic koto was tuned primarily in the key of D minor/F major (D-E-F-G-A-Bb-C), which also allowed us to perform in the key of A minor/C major as well (C-D-E-F-G-A-B) by simply raising the Bb string up by one half step. Both of the live kotos were amplified via contact mics which were then fed into the Eurorack system, thereby allowing them to make use of the effects and filters easily. The entire performance was captured in a 12-channel audio recording and filmed for presentation at the New Interfaces for Musical Expression (NIME) conference in Mexico City from May 31-June 3 as part of the Music track.

4.3 Third Performance

The second public presentation of our performance method took place at Bar Transit in Hiyoshi on July 21st. This performance consisted of three performers on Eurorack synthesizer, koto, and erhu. The performance consisted of six songs and lasted approximately one hour. Of the six songs, three were performed previously but modified. In addition to the application of the average BPM of the performers from the previous concert, we also utilized EDA which was applied to various elements of the Eurorack system. Finally, we gave the first trial of a visual graphic score. In this graphic score, a large slider indicates how excited or calm the performers and audience are, and this is then used as a visual indicator for the performers to interpret freely.

(1) 1. *Ringing*: From the previous performance, yet this time we applied the average BPM of the audience to the tempo and the EDA was applied to the wet/dry signal of the Eurorack effectors.
(2) 2. *Traditional Song*: From the previous performance, but with one solo koto player. Eurorack parameters were manipulated manually based on the visual feedback.
(3) 3. *Chorale*: From the previous performance, this piece used average BPM for the tempo of the song and EDA for the density of the synthesizer oscillators. The visual score was used to guide the performer in terms of dynamic range.
(4) 4. *Floating Like Dust*: This song did not use physiological data for any sonic manipulation, but instead the visual score guided the intensity and form of the song.
(5) 5. *Spectral Voices*: This song featured two performers singing improvised melodies based on the visual score while the performer BPM and EDA controlled the intensity of the Eurorack effectors and the speed of the LFO.
(6) 6. *Lioness*: From the previous performance, this song used the average BPM of the performers as the tempo indicator and EDA as the control of the feedback in the Eurorack effectors.

In this performance, the robot koto was tuned as it was previously (D minor/F major or A minor/C major). One of the new songs, *Floating Like Dust*, was in the key of D major, so the decision was made to omit the robot koto from this song.

5 OBSERVATIONS

5.1 Physiological Data Example

In order to support our choice of the physiological data metrics we present the data from the first performance as an example. Although the focus of this paper is the conceptual framework and methodology, we think it is necessary to exemplify and explain our choice of the physiological data metrics. We modeled some of our data analysis methods after the performance analysis found in a related study which analyzed the data from audience members of a dance performance [11]. In-depth analysis of these three performances along with others will be performed later. For the sake of completeness, summary plots for the other two performances are presented in the appendix. All the data gathering was approved by the university ethics committee and was done in accordance to the university guidelines and local legislation.

5.1.1 Heart Rate Variability Data. As shown in Fig.4. Top, we recorded Root Mean Square of Successive Differences (RMSSD) between consecutive heart beats in milliseconds as a metric of heart rate variability. It is known to be correlated to parasympathetic nervous system activation, meaning that the increase in RMSSD can be attributed to a more calm or relaxing experience. In the presented data we can clearly identify an increasing trend towards the end of each song. Average RMSSD in the beginning of all 5 songs is 48.82 (STD: 13.77), while in the end it is 58.29 (STD:14.45). Two-tailed T-test shows significance with p=0.001. One interesting point in the HRV data can be seen around minutes 5-8, in which the audience's HRV gradually drops down together, signifying a less relaxed state. These moments correspond to the gradual introduction of each performer (robot koto, then guitar, then the koto players).

5.1.2 Electrodermal Activity Data. In the EDA data shown in Fig.4 Bottom, we clearly see an increase in the EDA activity at the end of each song. Abnormally high activity is observed at minutes 1, 11, 18, 26 and 31 (Z-score over 1.5). Interestingly, most of them occur on the transitions between the songs (minutes 11, 18, and 26). These three data points can be attributed to the audience clapping and the noise it causes. However, the sudden increase in EDA activity at minute 1 matches the timing when the robot koto starts to play. Minute 31 corresponds to when the robot koto began to play at an accelerated rate. Each of the 13 solenoids gradually started to activate faster and faster, until all were activated at 20ms intervals, producing an extremely loud noise. This gesture lasted roughly 1 minute and then gradually faded out at the end.

While this data is only a preliminary analysis, we believe that it shows the potential for a novel and unique outcome when performing with physiological data, even though the application may not be explicitly understood by the audience.

5.2 Post-Performance Interviews

After each performance we conducted a formal interview with a pre-defined list of questions with the performers, mostly using binary choices and yes or no questions. Performers gave explicit consent to be interviewed and the data gathering was approved by the ethics committee. In the post-performance interviews with the performers, they all stated that they felt like the second performance felt more natural and engaging. This could very well be due to the fact that it was the second performance on the same day and they may have just felt more comfortable due to being warmed up. This is something that we will investigate more thoroughly in the future. It was also stated that in the second performance, there were small moments where the adjusting tempos were felt more strongly. One of the performers specifically stated that this feeling was interpreted as more organic than performing without the average BPM data driving the tempo. This will also need to be further investigated to validate. It was also stated by all performers that having this bespoke robotic music instrument performing alongside them without any visible human intervention gave them a new sense of performative inspiration. This could be due to the fact that we are used to seeing humans performing instruments but when it is a seemingly autonomous object playing with us, it can inspire a new sense of collaboration. Although we cannot say certainly that this is the contributing factor, we will further analyze and investigate this area.

5.3 Performer/Composer Interviews

We interviewed five external performer/composers in order to gain more insights and perspectives into what they would like to see in this kind of method and how we can shape the method to better accommodate a wide range of performance philosophies. These interviews were intended to inspire us to optimize design feedback surveys for a much larger inquiry into how we can shape this method in the future. The interviews were conducted in the form of a survey with yes or no questions. On each response, the participants were asked to elaborate on their reasoning in writing. All the participants gave their explicit consent to be interviewed and were informed that their responses would be recorded and used for publication. All the data gathering was approved by the ethics board.

Of the responses we received, the average age was 38.4 years of age, with 29.8 years of musical training, 22.8 years of performing live, and composing music for 15 years (one responding musician does not compose music). We asked them a series of questions regarding our method for physiological sensing and live performance, and how this method might be applied to composition. These questions revolved around how they might apply this kind of method, what sort of concerns they may have, and how it might change their overall approach to performative expression. Below are some of the highlights from these interviews:

(1) In response to whether or not the performers would find a visual indicator of the performers' physiological data, all the composers who prefer performing over recording music (3 of them) in their practice expressed that they are interested to know other co-performers relaxation/excitement levels through visual indicators. This was seen more as an extension of the performance itself. However, most of the musicians (4 out of 5) showed hesitation to this due to the fact that it might distract them or cause them to focus too much on the audience and not on their performance. Yet the audience feedback during live performance is also not the focus of this work. Only one musician who prefers recording music over performing mentioned she would like to see audience data while feeling no need to see other performers. This also showed different preferences in live performing could lead musicians to be interested in different aspects of applying our system.
(2) Regarding the kind of visual cues they would prefer to see, all responses indicated they would prefer a more vague or graphic score as opposed to any kind of traditional notation.

Figure 4: Example data from the first Performance. Top: RMSSD metric of HRV of all subjects, outliers with Z-score over 1.5 are removed. Bottom: number of Phasic EDA peaks per minute for all the subjects.

This would allow them to create more freely and in line with established improvisational methods.

(3) Two of the responses indicated that they are somewhat attentive to the audience during performance while the other three stated that they have little to no focus on the audience. However, all five stated that they are very attentive of the other performers, whether through visual observation or by listening and responding to their musical gestures.
(4) All musicians agreed that they were very interested in performing alongside an artifact which would represent physiological data. One response indicated interest in this artifact showing the audience data, while the other four preferred to only have it embody the performer's data.
(5) The four composers of the group all indicated that they would be very interested in using this system for composing music. One response indicated uncertainty in using it live but instead would prefer to record data and allow that to create a graphic score to then perform live.

6 LIMITATIONS AND FUTURE WORK

One of the biggest limitations with the bespoke robot koto is the limited range of expressive capabilities. Human koto players are able to bend and pluck the strings in many different ways, whereas the current koto design affords only one type of pluck and one type of string bend. In the new design, we are seeking to expand the actuation methods to allow a broader range of performative possibilities. Another limitation with the current koto design is the loudness of the solenoids. When the robot koto is playing by itself, hearing the resonating strings is rather easy. However, when other musicians are playing along, these strings resonances become quite difficult to discern. Beginning with our first live performances, we amplified the koto via a contact mic and used a band pass filter to improve the amount of string resonance vs solenoid sound. This still proved to be an undesirable mixture. In the new design, we are changing to quieter actuation methods to improve the noise to resonance ratio.

In terms of performative limitations, the biggest drawback with our current method is the lack of a cohesive visual representation. While we have begun to experiment with a visual indicator/score, it is still in its early stages. This would give the performers a more direct indication of the incoming physiological data and allow them to express more freely and directly with the system.

Moving forward, we intend on doing a much more thorough analysis of the data from these and future performances to better understand the consequences and impact of performer and audience data in live performances. As we continue to develop and refine our method, we wish to gain more insights into what this data means and how that might shape the future of this project. At this stage we focus on the performers and how they can utilize the novel technology we propose, however once the design flow is polished, we will focus on the evaluation of such performances from the spectator's perspective.

7 CONCLUSION

Our proposed method is a multi-modal approach to performance and composition which relies on the intrinsic interpretation and exploitation of physiological data as a means for creating a novel approach to live music. This method is deeply rooted in the traditions of live improvisation and the integration of a sensing platform which can relay this information in an easy-to-use format for implementation into an artifact system consisting of bespoke musical objects and analog synthesizers. All of these elements are controlled and constrained by a Max/MSP patcher which relays the physiological data and controls the instruments in a manner which still allows the intervention and manipulation of the performers.

This work began from an essential need to develop a system which would allow the performers and composers to express themselves in new ways through this physiological data acquisition. Regardless of the methods or applications of the data, the performance and composition itself has always and will always be at the forefront of system. Our investigations began in earnest with the design and completion of our robotic koto, which served as the starting point for our exploration. Upon realizing this instrument, we set out to devise a method for incorporating physiological data within this instrument and integrating it into a live performance setting. While the initial investigation was centered around this robotic instrument, the more fully realized method became the main focus of our work. The robotic koto was on piece of this comprehensive artifact system in which performers and composers could explore new sonic possibilities. The main role of the koto in this work was to serve as an interface between fully digital physiological data and relevant statistical metrics and live human performers. This way we can achieve a more organic performance flow, where the human musicians can improvise around what the koto is doing and vice-versa.

The process of composing for this kind of performance method proved to feel more natural than expected. In the beginning, we felt as though these kinds of restrictions in performance and composition might hinder the work itself. However, through the live application of this system, as composers we found it to be rather liberating. These limitations provide a more comfortable space for improvisation and interpretation for the performers. When the performers are not bound to strict notation but are given a set of boundaries in which they can explore freely, it hearkens back to some previous improvisational traditions such as jazz music or figured bass.

In all, these performances gave us clear insights into how we wish to proceed with developing our method of embodied live music. While our initial ideas seemed to suggest that applying physiological data would be a rather direct connection, our findings and impressions of the performances suggest that applying this real-time data in a more obscured and intentionally blurry manner would lend itself more to freedom of expression and interpretation for the performers. Instead of attempting to directly tie the physiology of performers or audience members to some kind of specific emotion such as happiness or uneasiness, simply providing this data as a new input method for interpretation could provide a much more expressively liberating method.

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A ADDITIONAL DATA SUMMARY

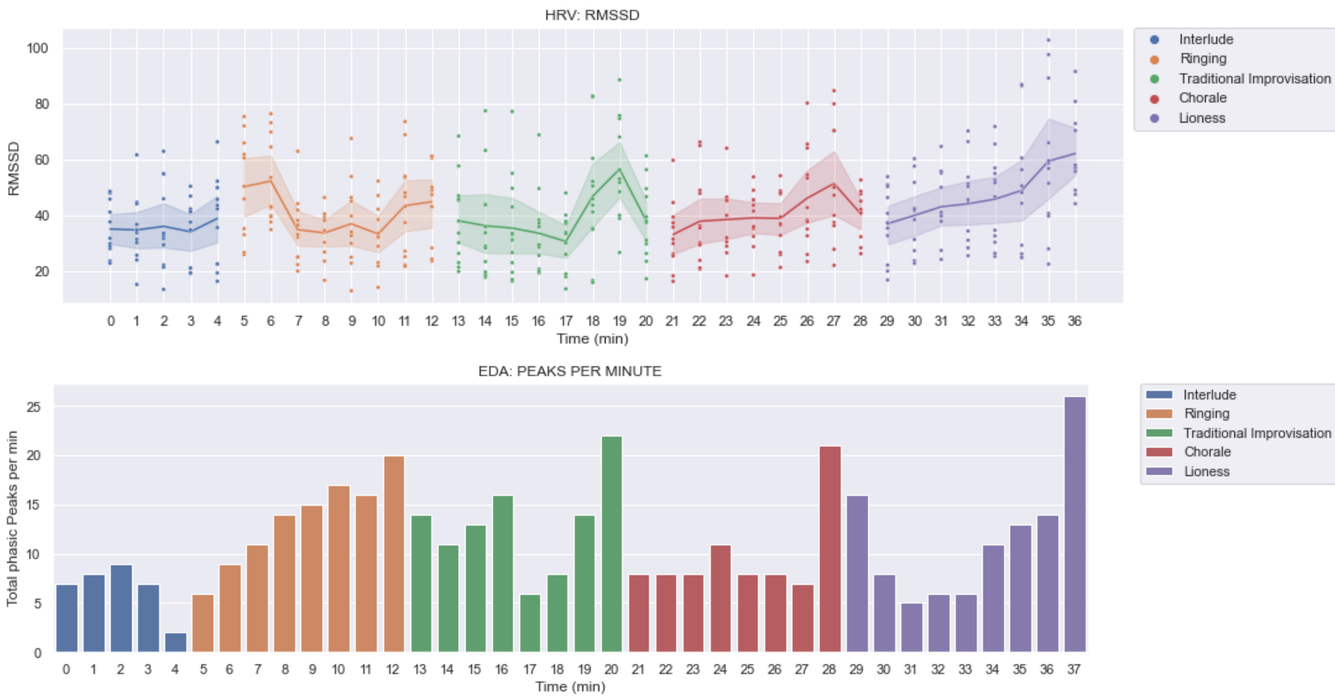

Figure 5: Summary data from the second Performance. Top: RMSSD metric of HRV of all subjects, outliers with Z-score over 1.5 are removed. Bottom: number of Phasic EDA peaks per minute for all the subjects.

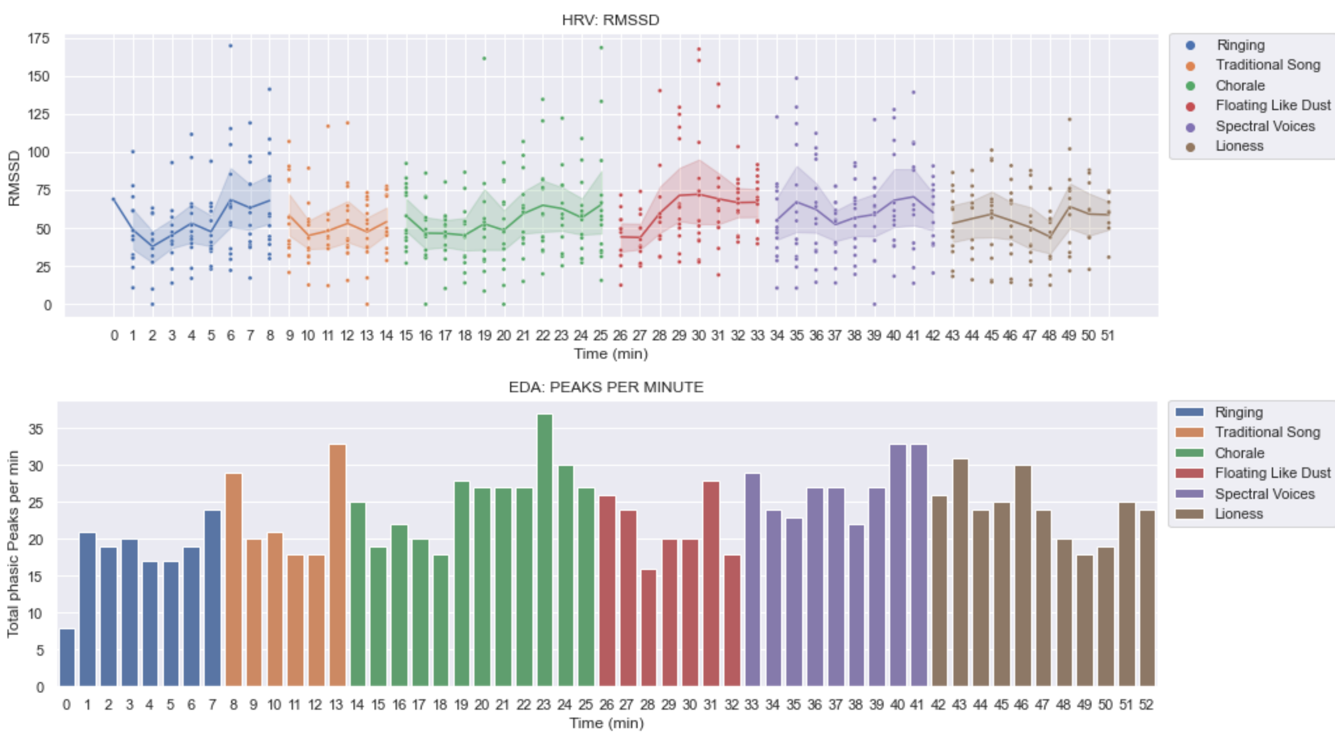

Figure 6: Summary data from the third Performance. Top: RMSSD metric of HRV of all subjects, outliers with Z-score over 1.5 are removed. Bottom: number of Phasic EDA peaks per minute for all the subjects.