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RESEARCH-ARTICLE

Snakeskin in the Wild: A Multi-Sensor Framework for Performance Art: A Case Study in Multimodal Sensor Synchronization

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Snakeskin in the Wild: A Multi-Sensor Framework for Performance Art:

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Abstract

This paper presents a lightweight software framework for synchronizing heterogeneous, wearable biometric devices during

live performance. Developed within the five-year interdisciplinary project Neurolive, a research collaboration that brings artists, scientists and audiences together to investigate “liveness,” the framework enables multiple EEG (Electroencephalogram) headsets, eye-tracking glasses, and other sensors to stream in real time over a unified clock. This version of the system was built for Neurolive’s third performance commission, ~ *snakeskin in the wild* ~ *created by Dog Kennel Hill Project (artists Ben Ash, Heni Hale and Rachel Lopez de la Nieta). Here are some creative interactions that emerged from this collaboration: (1) a stage-adapted P300 routine, (2) a spatialized EEG sonification sound-scape, and (3) audio cues to section the



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performance. We describe the concept, technical architecture, and artistic motivations, highlighting how the design prioritizes reliability, performer mobility, and network scalability inside a mid-sized performance venue. Field observations reveal practical challenges—setting up the EEG to stream via LSL, calibration drift—and the tactics adopted to maintain a “seamless” aesthetic. We conclude with lessons learned and recommendations for creators seeking to incorporate large-scale biosensing into immersive performance.

CCS Concepts

- Human-centered computing → Ubiquitous and mobile computing systems and tools;
- Human-centered computing → Interaction techniques;
- Software and its engineering → Real-time software;
- Hardware → Sensors and actuators.

Keywords

EEG, performance art, wearable tech, sonification, LSL

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Figure 1 Ben Ash wearing a sensor kit [Photo by Paula Puncher]

1 Introduction & Motivation

Live performance offers a unique laboratory for exploring reciprocal relationships between bodies, audiences, and machines. Yet capturing rich psychophysiological data in-the-wild, outside controlled lab conditions, remains technically demanding. Our goal is to make multimodal sensing simpler for artists while retaining the experimental rigor required by human-computer-interaction (HCI) researchers.

The work reported here stems from an ongoing collaboration between choreographers, neuroscientists, software engineers, and

experts in wearable computing. This is part of the ERC-funded Neurolive project (www.Neurolive.info). Recent studies suggest that movement synchrony among performers can predict neural synchrony in spectators, highlighting the importance of real-time embodied dynamics in shared live experiences [1]. Similarly, audience physiological responses have been directly linked to choreographic choices in dance [5]. A recent finding of the Neurolive project uncovered links between audience brain synchrony, choreography and the live experience [7].

2 Artistic Context

~ *snakeskin in the wild* ~ (performed at Siobhan Davies Studios, London, November 2024) by Dog Kennel Hill Project brings their combination of formalism and anarchy to the examination of liveness and the aesthetics of science. With closely integrated artistic and scientific experiments, the performance confronts head-on the slippery task of attempting to measure liveness in the live performance context instead of controlled lab conditions.

3 Technical Setup

Deploying a multimodal experiment of this scale requires state-of-the-art equipment and robust middleware to coordinate communication across devices. Below we outline the key components of our setup.

3.1 ANT Neuro’s Eego Sports

The eego Sports system is a mobile EEG kit designed for high-performance recordings in real-world environments. It includes a 32-channel EEG electrode cap and a respiration belt, both connected to a compact amplifier (Figure 3). The amplifier streams data at 500 Hz to a Windows Surface tablet. The version of the software we had access to was originally designed for single-device operation, so to accommodate our unique multi-device hyperscanning setup, we developed a standalone executable that bypasses the existing interface and streams raw amplifier data directly via Lab Streaming Layer (LSL) [2].



Figure 2 EEG Setup Section [Photo by Paula Puncher]

3.2 Pupil Labs Invisible

The Pupil Invisible eye-tracking system includes a 1088×1080 px scene camera (30 Hz), two 192×192 px infrared eye cameras (200 Hz), an onboard microphone, and a 200 Hz IMU (accelerometer + gyroscope). We used the Pupil Labs Realtime Network API [6] to control all devices programmatically: initiating and stopping recordings, monitoring device status (battery, connection, activity), and sending time-synced markers using a custom time echo protocol for alignment with EEG streams.

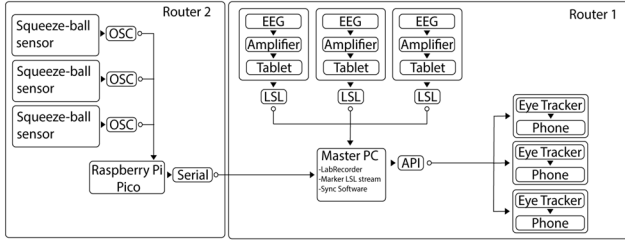


Figure 3 illustrates the data flow and router allocation (here shown for 3 devices, in practice it can handle 20+)

3.3 Custom Squeeze Ball

We use a custom made ‘squeeze ball’ device to monitor audience engagement. Each squeeze sensor consists of a pressure sensor embedded in a foam ball, housed in a wooden shell that includes an ESP32 microcontroller, battery pack, and status LED [4]. These devices communicate over a dedicated Wi-Fi network (router 2) using OSC messages. A central Raspberry Pi Pico receives the OSC data and relays it via USB Serial to the master computer.

Table 1 shows the 3 main sensor systems and protocols: EEGO Sports from AntNeuro , Invisible eye tracker from Pupil Labs , and our custom-built Squeeze ball for providing audience feedback [4].

3.4 Custom Synchronization Software

All devices broadcast to a master computer running our custom middleware, developed in Python. This central system coordinates data acquisition, time synchronization, and stream management across the sensor network. It also includes a lightweight user interface (GUI) designed for live performance control.

The GUI enables real-time monitoring of system components, including:

1. Eye tracker status (connection, battery, recording state);
2. A live log of recently sent markers.
3. Customizable user-triggered buttons for sending predefined markers to devices.
4. Controls for starting and stopping performance sections, each accompanied by a synchronized audio cue

This layer of interactive control proved crucial in rehearsals and performance, allowing the scientific team to remain responsive and flexible while maintaining synchronized data collection.

Device	Qty	Protocol	Measurement
Eego Sports	≤ 10	Lab Streaming Layer (LSL)	Scalp EEG (32 channel)
Pupil Invisible	≤ 20	HTTP REST WebSocket	Gaze & blinks
Custom Squeeze Ball	≤ 20	Wi-Fi OSC USB-Serial	Audience engagement

Table 1. Overview of sensors, protocols and measurements

4 Creative Applications

4.1 P300



Figure 4 P300 section [Photo by Paula Puncher]

The performance includes an adaptation of the classic P300 paradigm to the live performance context [3]. After participants are equipped with wearable sensors, the room transitions from a functional arrangement for EEG set-up to a square-shaped stage area. This spatial transformation is marked by subtle scenographic shifts and a constant rhythmic beeping emitted from the speakers — a cue for both performers and the scientific team that the experiment is about to begin.

Once all systems are ready, a performer introduces the audience to the concept of the P300, a type of event-related potential in brainwave activity associated with attention and expectation. Immediately afterward, the live P300 test commences using two alternating tones: a frequent “standard” tone and a rare “oddball” tone.

The center of the performance space features an installation with a ceramic vase, topped by a head of cabbage, over which slime slowly drips (Figure 4). First, the vase is concealed by dark panels for 3 minutes. The room gets dark with white lights focusing on the vase. Then performers slide the panels away to reveal the installation to the audiences. Audience members are then able to see the installation for 3 minutes and are instructed to count the number of oddball tones during this time.

The size of the P300 effect is computed by subtracting EEG responses to the frequent beeps from the infrequent ones. The P300 is typically used as an index of attention, that is especially relevant in real-world neuroscience experiments, and can be used to validate the synchronisation technology as it occurs at a specific latency.

4.1 EEG Sonification

Live EEG sonification fulfilled both scientific and artistic purposes. Making audiences aware that the sound heard during various sections of the performance was directly related to real-time brain signals – their own, other audience members’ or performers’ – was an important factor in the experimental design. Each EEG-wearing audience member was given a unique identifier and was assigned to a specific experimental group. These groups experienced the parts of the performance differently from each other and received specific information. As, in one section, some audience members wearing EEG were told their brain activity was now being sonified.

Artistically, the live EEG sonification provided additional material for the performers to work with both in terms of choreographic design and live improvisation. The sound design aimed to convey an intuitive sense of brain activity, and utilised an 8-channel surround sound speaker system to create an immersive sonic environment. Three main strategies were employed: audification, the sonification of synchrony, and the sonification of power-spectral density. Audification involved directly translating EEG signals into auditory signals, and was used for a solo dance section of the work. The geometrical layout of sensors on the head was used to map each electrical signal in 360 degrees around the performance space. Low-pass filtering and subtle pitch shifting were employed to enhance the sound of the raw EEG. Synchrony was sonified by mapping correlations between averaged EEG signals from multiple participants to sine wave oscillators. Power-spectral density used the power of different EEG frequency bands to control the density of impulses connected to a bank of resonant filters, tuned at intervals proportional to EEG frequency bands.

4.2 Audio Queue

Each section of the performance was marked by a distinctive audio tone, identical to the one used in the earlier P300 sequence. This consistent auditory signal served a dual purpose. For performers, it functioned as a temporal anchor, allowing them to transition between choreographic segments with precise timing without relying on visual or verbal cues. For the technical system, the tone acted as a synchronization marker: a precisely timed event that was simultaneously logged across all connected devices. These markers provided crucial sectioning between experiments, allowing the researchers to align multimodal streams (EEG, eye tracking, and sensor input) to specific moments within the performance timeline.

5 Challenges

5.1 Hardware Limitation

The EEGO mobile EEG kit uses a Windows Surface tablet as its data collection unit, with a single USB-A port serving as the connection to the amplifier. This physical connection proved mechanically fragile, particularly in mobile or semi-immersive setups. If the amplifier becomes disconnected for more than 30 seconds, the official software terminates the data recording session automatically. To circumvent this, we bypassed the official

software after impedance checks and established a continuous raw data stream using our custom LSL-based solution.

5.2 Eye Tracker API Saturation

During large-scale tests involving 26 eye tracking devices, our initial approach created a new thread for each API message sent to individual devices. While message transmission itself remained stable, the system became overloaded by the creation and termination of threads, leading to resource exhaustion and dropped messages. The solution was to maintain a persistent thread per device, initialized at the start of the recording session and killed at the end of the recording and reused for all subsequent communication. This reduced overhead and allowed the system to scale more reliably.

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6 Recommendations

For multisensory experimentation in live performance contexts, particularly those conducted outside controlled laboratory conditions, we recommend the following technical practices:

Unify all sensor streams using a common protocol like Lab Streaming Layer (LSL). LSL handles time synchronization across multiple data sources by aligning them to a shared internal clock, which greatly simplifies downstream analysis. Use an LSL marker stream to annotate and identify performance sections in real time. This is something we implemented in Neurolive Performance 4, and streaming via LSL: Audio channel, video frames, on top of the EEG stream.

Avoid Bluetooth for time-critical data. While Bluetooth is useful for mobility, it is notoriously difficult to synchronize across devices, especially when internal clocks drift or message delivery becomes unreliable under network congestion.

Bridge incompatible protocols into LSL. If a device relies on another protocol (e.g., HTTP API, OSC, Serial), implement a lightweight LSL relay. This relay should capture the raw data from the source and re-stream it via LSL with accurate local timestamps. Doing so ensures consistent time alignment between different physiological signals.

7 Future Work

The performance ~ snakeskin in the wild ~ was presented over three days, with two performances per day, resulting in a substantial multimodal dataset. We are currently in the preprocessing phase, aligning and cleaning the data for subsequent analysis. Looking ahead, several improvements to the synchronization software are planned. One of the main areas of development involves refactoring the GUI using a modern web-based framework such as React [8]. This transition would offer multiple benefits:

1. The potential to offload some processing to a secondary computer, while maintaining real-time UI control from the master system;
2. The ability to create dedicated monitoring dashboards for scientists to track device status (e.g., EEG signal quality, eye-tracker battery levels, marker log activity);
3. A more intuitive and flexible user interface;
4. Easier integration of audio-based cues

However, it is important to note that decoupling the UI from the middleware (e.g., using an API call from the browser to the backend) may introduce additional latency in marker delivery. This is particularly critical for time-sensitive events like audio cues, where markers must be sent slightly in advance to ensure temporal alignment.

Further development is also underway to create an LSL relay for the Pupil Labs Invisible eye trackers, enabling their data to be streamed directly into synchronized LSL timelines without relying on post-hoc alignment. Two potential architectural approaches are being explored:

1. Middleware-integrated relay: Incorporate the LSL relay directly into the existing Python-based middleware, assigning a dedicated thread per device for receiving and forwarding data via LSL.
2. On-device Android relay: Develop a lightweight Android application to run directly on the phone connected to each Pupil Invisible Android device relaying the API data via LSL.

Both approaches present trade-offs in terms of latency, reliability, and deployment complexity. That said, this workaround may not be necessary for researchers adopting newer eye-tracking hardware, as the Pupil Invisible line has been discontinued in favour of the Pupil Neon, which offers native LSL streaming support.

8 Conclusion

This paper demonstrates that low-latency multimodal biosensing is achievable in live performance contexts and across multiple audience members and devices. By integrating EEG, eye tracking, and audience interaction sensors into a unified real-time system, we enable real-time interactions between audience's member brain wave signals and the performance. The software modular design, developed and tested in a real-world context, shows that scientific experimentation and artistic practice can meaningfully co-exist within a single technical framework. We hope this work contributes toward lowering the barrier for other artists and scientists seeking to embed biometric signals in performance and installation environments.

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References

- [1] Orgs, G., Vicary, S., Sperling, M., Richardson, D.C., Williams, A.L. (2024). Movement synchrony among dance performers predicts brain synchrony among dance spectators. *Scientific Reports* 14, 22079 <https://doi.org/10.1038/s41598-024-73438-0>
- [2] Christian Kothe, S.Y. Shirazi, Tristan Stenner, David Medine, and Christian Boulay. 2024. The Lab Streaming Layer for synchronized multimodal recording. *bioRxiv*. <https://doi.org/10.1101/2024.02.01.577479>
- [3] Ladouce, S., Donaldson, D. I., Dudchenko, P. A., & Ietswaart, M. (2019). Mobile EEG identifies the re-allocation of attention during real-world activity. *Scientific Reports*, 9(1), 15851. <https://doi.org/10.1038/s41598-019-51996-y>
- [4] Stamm JC, Richardson DC, Ward JA. Squeeze and Slide: Real-time continuous self-reports with physiological arousal to evaluate emotional engagement in short films of contemporary dance. *Extended Abstracts of the CHI Conference on Human Factors in Computing Systems 2024 May 2* (pp. 1-7) <https://doi.org/10.1145/3613905.3651886>
- [5] Han J, Chernyshov G, Sugawa M, Zheng D, Hynds D, Furukawa T, Padovani Macieira M, Marky K, Minamizawa K, Ward JA, Kunze K. Linking audience physiology to choreography. *ACM Transactions on Computer-Human Interaction*. 2023 Mar 7;30(1):1-32. <https://doi.org/10.1145/3557887>
- [6] Kassner, M., Patera, W. and Bulling, A., 2014, September. Pupil: an open source platform for pervasive eye tracking and mobile gaze-based interaction. In *Proceedings of the 2014 ACM international joint conference on pervasive and ubiquitous computing: Adjunct publication* (pp. 1151-1160). <https://dl.acm.org/doi/abs/10.1145/2638728.2641695>
- [7] Rai, L.A., Lee, H., Becke, E., Trenado, C., Abad-Hernando, S., Sperling, M., Vidaurre, D., Wald-Fuhrmann, M., Richardson, D.C., Ward, J.A. and Orgs, G., 2025. Delta-band audience brain synchrony tracks engagement with live and recorded dance. *iScience*. <https://doi.org/10.1016/j.isci.2025.112922>
- [8] Facebook Inc. 2024. React – A JavaScript library for building user interfaces. <https://react.dev>