Simulacra Naturae: Entangled Biomes

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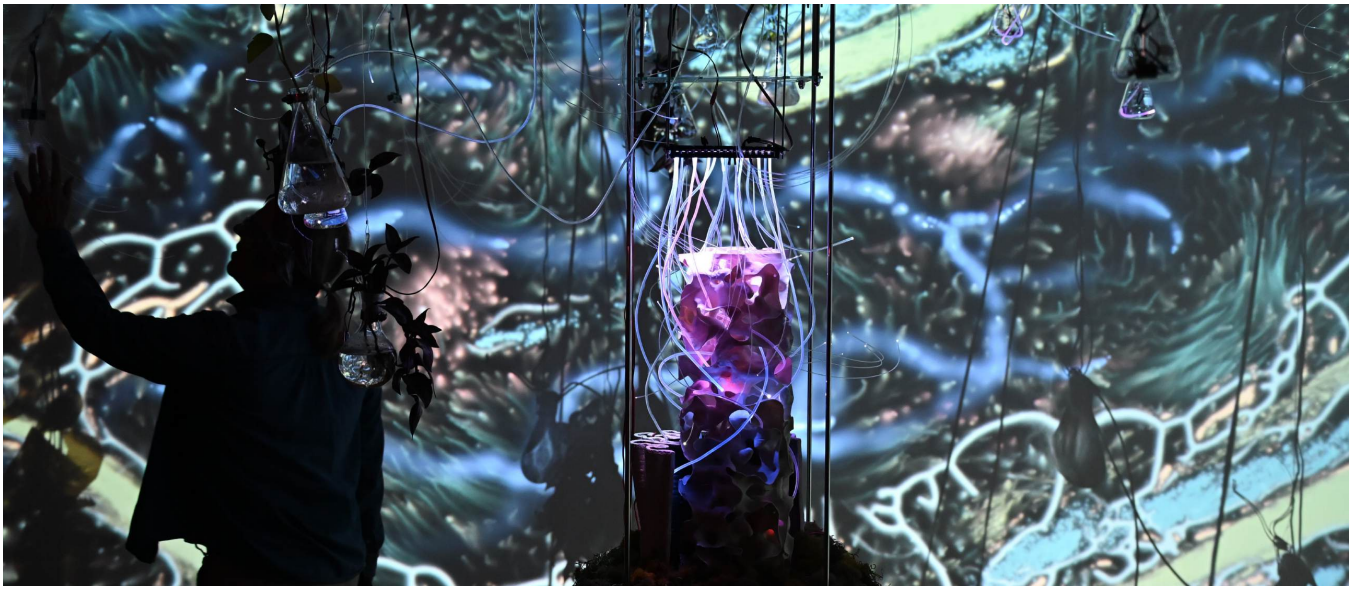


Figure 1: A photograph of the installation of Simulacra Naturae: Entangled Biomes, capturing five biomes that create a cyberphysical ecosystem featuring organic, artificial, and computational elements.

Abstract

Simulacra Naturae: Entangled Biomes operates as a multisensory infrastructure investigating how aesthetic experience emerges when biological activity, generative algorithms, and embodied agents interact. Action potentials from 131 neurons in brain organoids, grown *in vitro*, provide the foundation of emergent aesthetic behavior across heterogeneous subsystems spanning the visual, the sonic, and the material. Touch and proximity sensing further engages human interactions with the cyberphysical ecosystem, driving the movement of artificial plant elements. The result is a cyberphysical ecology where distributed neural dynamics and human interaction co-evolve across varying temporal and material scales.

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CCS Concepts

• **Applied computing** → **Media arts**; *Sound and music computing*; • **Human-centered computing** → *Collaborative interaction*; • **Computing methodologies** → *Procedural animation*; • **Computer systems organization** → *Sensors and actuators.*

Keywords

Agent-Based Modeling, Organoid Intelligence, Embodied Interaction, Bio-Digital Morphogenesis, Cyberphysical Ecology

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1 Introduction

We present our installation of *Simulacra Naturae: Entangled Biomes*, a cyberphysical ecosystem composed of distinct yet interconnected

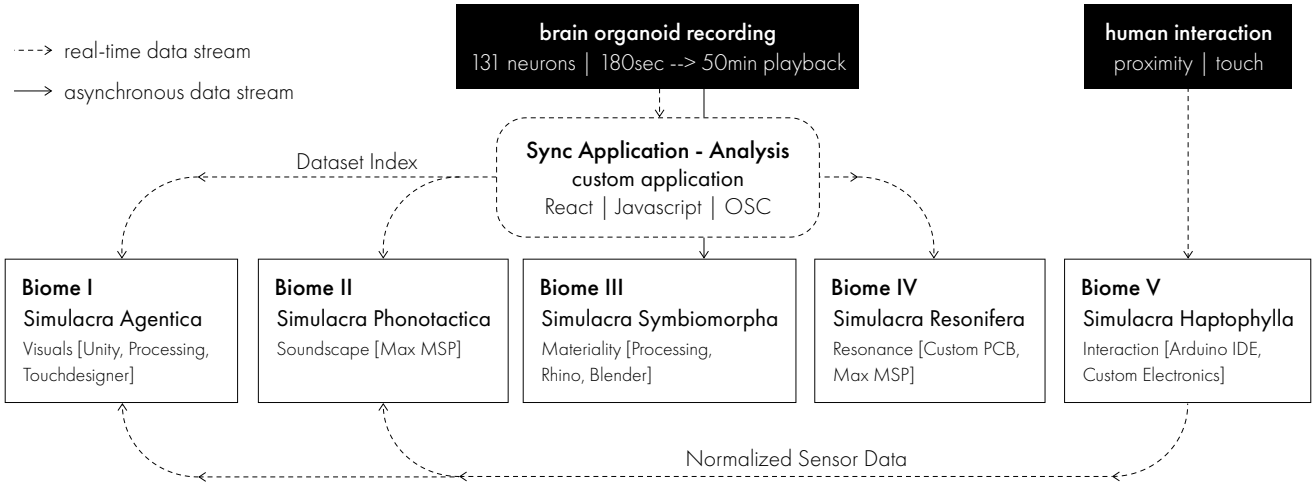


Figure 2: The system architecture of Simulacra Naturae: Entangled Biomes, where brain organoid data and human interaction affect the five biomes (visuals, soundscape, materiality, resonance, and interaction).

sensory experiences, partitioned into five biomes. Each biome translates organoid neural activity into a distinct sensory domain: visuals (Sec. 3.1), soundscape (Sec. 3.2), materiality (Sec. 3.3), resonance (Sec. 3.4), and interaction (Sec. 3.5). As a whole, the ecosystem challenges the traditional separation between biological, digital, and physical domains. Proximity and touch sensing from human interactions, as well as biological data from *in vitro* brain organoid cultures, modulate the visual projections, sonic environment, and feedback loops within the ecosystem.

This installation is our representation of how such a cyberphysical system may coexist and communicate with human observers. A question central to this installation is how we can create an environment shaped by computational and mechanical processes that both remain accessible to human interactions via perception and sensation, as well as inspiring or evoking emotional human responses. The work uses pre-recorded neural activity from brain organoids, three-dimensional clusters of lab-grown neurons [Sharf et al. 2022; van der Molen et al. 2025], as one layer within a larger generative ecosystem. The action potentials produced by 131 neurons, captured via electrophysiology, are treated as co-creative influences that modulate the behavior of interconnected systems over time, rather than deterministic inputs. Our interests lie in whether interactions with such a system could feel responsive or alive, or whether the system can induce affective states in human observers, without relying on direct narrative or anthropomorphic representation. Instead of building a fixed audiovisual composition, we designed conditions where multiple processes could continuously shape one another. Neural activity influences agent behaviors, AI-generated imagery, sound structures, lighting relationships, and physical resonances throughout the installation.

We build on a prior iteration of this work [Manoudaki et al. 2025] that featured two distinct biomes. The first biome was filled with live tropical plants and a floor-level projection layer featuring real-time generative AI visuals driven by brain organoid data, inviting participants into a sensory field shaped by nonhuman cognition. The second biome consisted of computationally fabricated clay sculptures embedded with solenoids, adding physical sound resonances to the generative surround composition. In contrast, *Simulacra Naturae: Entangled Biomes* presents five distinct biomes, depicted in Fig. 2, and takes further inspiration from artists and designers of generative and interactive systems, such as Ji and Wakefield [Ji and Wakefield 2015] and Beesley [Beesley 2020].

2 Materials and Implementation

2.1 Data

The recorded data is 180 seconds of spontaneous action potentials from human brain organoids, grown *in vitro* from induced pluripotent stem cells (iPSCs) by the Kosik lab at UCSB [Sharf et al. 2022; van der Molen et al. 2025]. Spontaneous firing from the organoids, sampled at 20 kHz, were spike-sorted to yield 131 active neuron channels that serve as the primary signal for the installation [van der Molen et al. 2023].

2.2 System Synchronization

The subsystems are synchronized through a custom application that handles real-time visualization and analysis of the organoid datasets. It parses two organoid recording files: one defining the spatial layout of the network (neuron IDs and their 2D X/Y coordinates) and another containing the temporal spike activity (millisecond timestamps mapped to firing neuron IDs). Once the data is loaded into the React-based front-end, the application reconstructs the neural web and simulates the action potentials across the timeline, generating dynamic real-time visualizations and identifying synchronized bursts of activity.

Beyond acting as a synchronization bridge, the application functions as the analytical core of the installation. It performs real-time feature extraction on the neural data—mapping topological relationships, tracking firing rates, and identifying complex macroscopic

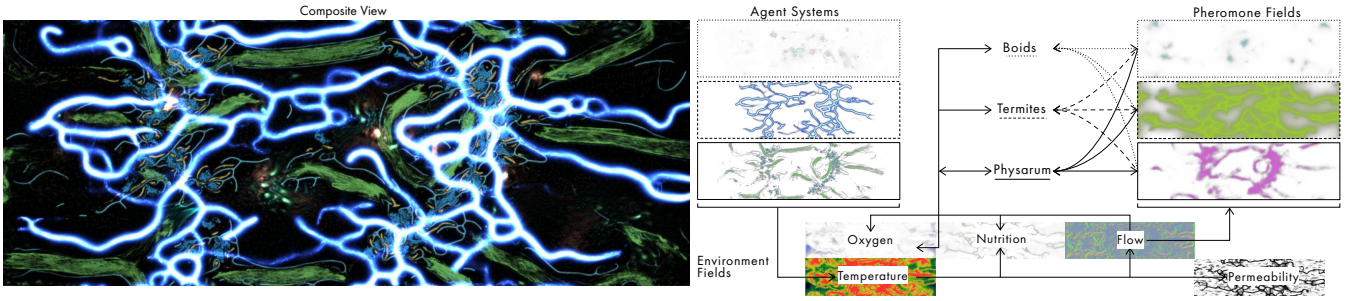


Figure 3: A diagram illustrating a selection of field interactions used in Biome I. (Right) Three agent systems read from and write to environment fields that drives their individual and collective behavior. (Left) The final projected output combines these agent systems in a composite view.

events like network-wide bursts. These extracted features drive both the digital and physical materiality of the installation. To synchronize the digital biomes, the application continually broadcasts its playback state over Open Sound Control (OSC) via a local Node.js bridge server. At each animation frame, the transmitted data index acts as a global counter, keeping all external processes (i.e., TouchDesigner, Unity, and Max/MSP) in lockstep. It also distributes the precise spatial features of the neural dynamics by sending the 2D coordinates of the neurons that most recently fired.

3 Biomes

The five biomes move beyond the representation of this data and towards emergent inter-systemic behavior.

3.1 Biome I

Simulacra Agentica (Visuals) is a real-time GPU compute ecosystem that translates organoid activity into a self-organizing artificial landscape. At its center is a shared scalar field forming the *environment*: a multi-channel substrate carrying nutrient, oxygen, temperature, and species-specific pheromone concentrations that diffuse and advect across the simulation space (Fig 3). Three populations of artificial life agents inhabit this field: *termite* agents are seeded at the recorded positions of the 131 organoid neurons, *physarum* agents lay chemotactic trails, and *boids* flock and forage. Each species reads the field through its own sensory and effector mapping, an *Umwelt*, governing how it follows local gradients, adjusts its speed, and deposits or consumes resources as it moves.

Neural activity is the system's primary driver. Action potentials are injected as localized stamps at each neuron's position, raising pheromone and temperature concentrations that diffuse outward and perturb established trails. Each agent also carries a firing state tied to the organoid recording: when their source neuron fires, it accelerates, deposits more intensely, and brightens. Because agents both read from and write back into the shared field, a form of stigmergy, local neural events propagate as cascading shifts in collective behavior rather than as direct one-to-one mappings.

The imagery is rendered directly from these accumulated trails (Fig 3). Species identity is encoded in hue, trail intensity and firing state in brightness, and temporal persistence through a motion-blur decay that leaves ghosted histories of movement. The layers compose into continuously evolving morphological structures that read as emergent rather than authored. Human interaction from Biome V and signals from the wider installation perturb the same field, keeping the visual landscape coupled to the organoids, the agents, and the visitors at once.

3.2 Biome II

Simulacra Phonotactica (Soundscape) is a four-channel generative composition, implemented in Max/MSP, that sonifies the organoid recording. Two features of the neural data structure the sound: the population firing rate and the temporal boundaries of coordinated network bursting events. The firing rate governs synthesis density and spatialization parameters, while burst endpoints cue harmonic transitions, producing a continuously evolving sound field structured by neural dynamics.

The harmonic foundation is a progression in C minor with Phrygian inflections, voiced through recordings of distorted electric guitar captured individually across the progression. These samples are treated with granulation, playback-speed (and thus pitch) manipulation, amplitude-envelope shaping, feedback delay, spatial distribution, and reverb, yielding two principal textures: sustained tones and clouds of granulated fragments. The density of sustained tones rises nonlinearly with the firing rate, whereas the granulated textures behave inversely, thinning as activity intensifies. Sine-tone drones and a subwoofer-routed kick anchor the low end, and each output channel carries its own reverb to reinforce the spatial character of the field.

3.3 Biome III

Simulacra Symbiomorpha (Materiality) turns the system's temporal dynamics into static physical form through computational fabrication. Parametric, laser-cut components frame the larger construction, while generative central artifacts are fabricated in ceramic and thermoplastic.

The central artifact is a ceramic vessel whose contour is generated by a differential growth algorithm [Thompson 1992], where a closed loop of nodes expands under competing repulsion and cohesion forces, inserting new nodes as it lengthens until the curve elaborates into dense, coral-like convolutions. Across the 180-second recording, each neuron's position and firing intensity set the local

growth rate: a firing event applies a spatially localized impulse with a quadratic falloff that briefly accelerates growth and tightens node spacing nearby. Bursts of neural activity therefore leave morphological traces, and the resulting form becomes a record of organoid behavior over the exhibition loop. For fabrication, the growing contour is sampled at regular intervals and layers are stacked into a single continuous spiral, exported as a toolpath for clay 3D printing. The vessel is printed in B-mix stoneware on a Potterbot 10 Super with a 5 mm nozzle, standing 500 mm tall with a 320 mm base diameter before firing, preserving neural perturbations in its walls.

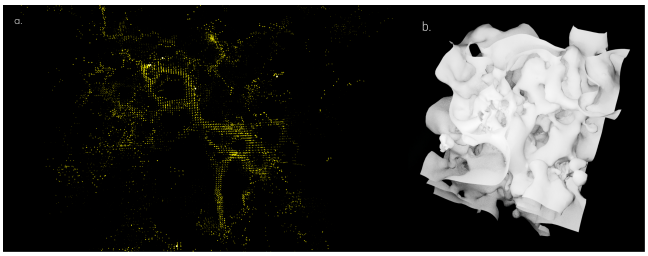


Figure 4: (a) Volumetric pheromone field accumulated by termite agents operating across a $100 \times 100 \times 100$ voxel lattice, shown as a point cloud prior to surface reconstruction. (b) Final mesh after editing and cleanup, prepared for segmentation into four print segments for fabrication.

Alongside the ceramic vessel, we materialize the termite trails from Biome I as a volumetric PLA form (Fig 4). The same agents follow their stigmergic rules across a $100 \times 100 \times 100$ voxel lattice, each sensing only its local neighborhood and steering towards higher concentrations [Codling et al. 2008], so the form emerges from accumulated traces rather than global plan [Camazine et al. 2003]. The deposits are then exported as a point cloud, reconstructed into a watertight surface via Poisson surface reconstruction, and refined with mesh editing to integrate compositionally with the ceramic vessel.

Together these artifacts are static compressions of the system's otherwise ephemeral behavior, holding the neural activity that animates the visuals and the soundscape as material objects that can be examined directly.

3.4 Biome IV

Simulacra Resonifera (Resonance) spatializes the biological processes. A subset of 27 strongly coordinated neurons is mapped onto solenoids embedded within the ceramic vessels and scientific glassware, each striking its vessel when its source neuron fires. The result is a spatially distributed instrument that articulates the threshold between the biological, the digital, and the physical.

3.5 Biome V

Simulacra Haptophylla captures interactions between human visitors to the exhibition and the artificial flora of the ecosystem. Three flexible artificial muscles, composed of electronic and fabricated components (Fig. 5A), were designed to resemble natural flora on the California coast.

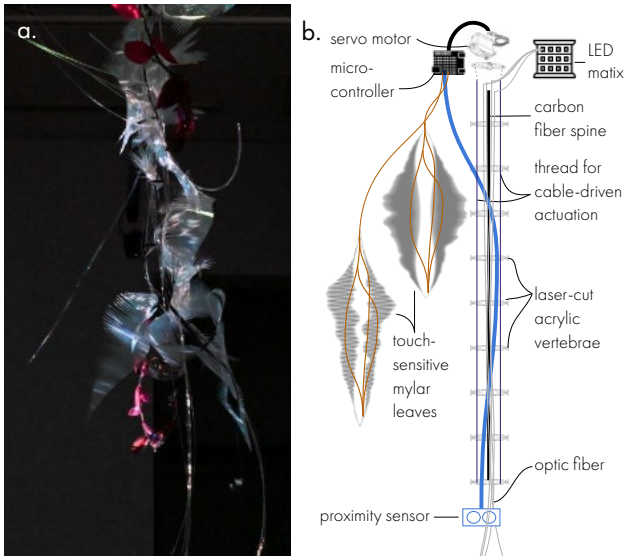


Figure 5: A) The artificial muscles integrate proximity and touch sensing. B) Fabricated components include a carbon fiber spine, laser-cut acrylic vertebrae, and machine-cut mylar leaves. Electronic components include a microcontroller, ultrasonic proximity sensors, capacitive touch sensing, servo motors, and an LED matrix. Icons from Noun Project (Arduino Board by Victor Bolivar CC BY 3.0).

Carbon fiber strips (3 mm thick) create the spine of each artificial muscle. Laser-cut acrylic pieces that resemble vertebrae are affixed to the carbon fiber spine via UV-cured adhesive, creating the channels for the cable-driven actuation mechanism and enabling machine-cut mylar leaves to attach to the carbon fiber backbone. Spectra PE line, chosen for its material properties, is threaded through each acrylic vertebrae of the carbon-fiber spine. When pulled by the horn of the servo motor, this thread causes the carbon-fiber spine to flex and move.

Each muscle combines capacitive touch and proximity sensing with cable-driven servo actuation. An ultrasonic sensor (Adafruit HC-SR04) in the spine detects proximity (Fig. 5B), and its reading, mapped to the 180° range of a servo (Deegoo-FPV MG995), drives the muscle's flexion. The feedback loop makes the muscles feel responsive to people walking past or reaching toward them. These interactions further inject perturbations into the organoid signal stream driving Biome I and Biome II, so visitors induce change through cross-biome feedback.

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References

Philip Beesley. 2020. *Kinetic architectures and geotextile installations.* Riverside Architectural Press.

Scott Camazine, Jean-Louis Deneubourg, Nigel R Franks, James Sneyd, Guy Theraulaz, and Eric Bonabeau. 2003. *Self-Organization in Biological Systems.* Princeton University Press, Princeton, NJ.

Edward A Codling, Michael J Plank, and Simon Benhamou. 2008. Random walk models in biology. *Journal of the Royal Society Interface* 5, 25 (2008), 813–834.

H Ji and Graham Wakefield. 2015. Endogenous biologically-inspired visualization immersed within an art of complex systems. *Proceedings of the IEEE VIS Arts Program (VISAP), Chicago, Illinois* (2015), 30–37.

Nefeli Manoudaki, Mert Toka, Iason Paterakis, and Diarmid Flatley. 2025. Simulacra Naturae: Generative Ecosystem driven by Agent-Based Simulations and Brain Organoid Collective Intelligence. In *2025 IEEE VIS Arts Program (VISAP).* IEEE, 29–36. arXiv:2509.02924 [cs.MM]

Tal Sharf, Tjitse van der Molen, Stella M K Glasauer, Elmer Guzman, Alessio P Buccino, Gabriel Luna, Zhuowei Cheng, Morgane Audouard, Kamalini G Ranasinghe, Kiwamu Kudo, Srikantan S Nagarajan, Kenneth R Tovar, Linda R Petzold, Andreas Hierlemann, Paul K Hansma, and Kenneth S Kosik. 2022. Functional neuronal circuitry and oscillatory dynamics in human brain organoids. *Nature Communications* 13, 1 (2022), 4403. doi:10.1038/s41467-022-32115-4

D'Arcy Wentworth Thompson. 1992. *On Growth and Form* (complete revised ed.). Dover Publications, New York.

Tjitse van der Molen, Alex Spaeth, Mattia Chini, Sebastian Hernandez, Gregory A Kaurala, Hunter E Schweiger, Cole Duncan, Sawyer McKenna, Jinghui Geng, Max Lim, et al. 2025. Protosequences in brain organoids model intrinsic brain states Authors. *bioRxiv* (2025), 2023–12.

Tjitse van der Molen, Alex Spaeth, Mattia Chini, Sebastian Hernandez, Gregory A Kaurala, Hunter E Schweiger, Cole Duncan, Sawyer McKenna, Jinghui Geng, Max Lim, Julian Bartram, Aditya Dendukuri, Zongren Zhang, Jesus Gonzalez-Ferrer, Kiran Bhaskaran-Nair, Lon J Blauvelt, Cole R K Harder, Linda R Petzold, Dowlette-Mary Alam El Din, Jason Laird, Maren Schenke, Lena Smirnova, Bradley M Colquitt, Mohammed A Mostajo-Radji, Paul K Hansma, Mircea Teodorescu, Andreas Hierlemann, Keith B Hengen, Ileana L Hanganu-Opatz, Kenneth S Kosik, and Tal Sharf. 2023. Protosequences in brain organoids model intrinsic brain states. bioRxiv. doi:10.1101/2023.12.29.573646