ChatGPT

Multimodal Closed-Loop Biofeedback Systems for Dynamic Audiovisual Environments

Experimental Research Systems (VR/BCI Prototypes)

- **FractalBrain (2024)** – A recent neuroadaptive VR experience using EEG to drive fractal geometries for mindfulness [1]. Wearing an Emotiv EEG and a Meta Quest 2 VR headset, users view ever-changing fractal patterns whose complexity, symmetry, and audiovisual parameters are continuously modulated by their brainwaves [2]. The EEG is analyzed in real time and mapped to visual and sound variables, creating a unique closed-loop experience for each user [2]. Pilot studies showed FractalBrain can facilitate meditative focus and attention enhancement [2]. *DonutOS Tie-In:* FractalBrain's geometric **Symmetry Forge**-like visuals and EEG-driven adaptation inform how **Intention Field** metrics (e.g. EEG alpha/theta power) can dynamically forge fractal symmetries in Symmetry Forge.

- **Closed-Loop VR for Attention** – Li *et al.* (2020) introduced a **closed-loop Attention Restoration Theory (ART)** system in VR [3]. Participants explored a virtual nature scene while an EEG-based algorithm monitored their vigilance (e.g. detecting mental fatigue via alpha) [4]. The VR content difficulty and scene "extent" were automatically adjusted in response to EEG metrics, keeping users at an optimal engagement level [5]. This is the first demonstration that a VR-HMD with real-time EEG feedback can enhance attention by adapting the environment on the fly [6]. *DonutOS Tie-In:* This neuroadaptive approach aligns with **Intention Field** goals – measuring attention in real time and altering VR "extent" or complexity to maintain a flow state. It leverages predictive coding: the system minimizes surprise by tuning stimulus complexity to the user's cognitive state, analogous to **Membrane locking** (locking into a stable, engaged state).

- **Multimodal Adaptive Cinema (2025)** – Xinye Xu *et al.* developed a closed-loop "therapeutic interactive cinema" that integrates EEG, ECG (heart/HRV), GSR (skin conductance), facial expression and posture tracking, plus gaze dynamics [7]. The system's *adaptive narrative controller* adjusts the audiovisual content of a film in real-time according to the viewer's emotional arousal and cognitive engagement [7]. For example, if attention wanes or stress rises, the movie's pace, scenes, or sound may change to re-engage and calm the viewer. In tests with older adults, the closed-loop film boosted HRV (~18%↑) and alpha synchrony (~12%↑) while stabilizing gaze and reducing facial tension [8] – indicating greater immersion and relaxation. *DonutOS Tie-In:* This project offers a blueprint for **Intention Field** and **Donuscope** overlays – unifying multiple biosignals to maintain user "coherence." The gaze-tracking driven scene adjustments parallel Donuscope's attention-guided overlays, and the cross-modal sensor fusion illustrates how **Membrane locking** could stabilize an experience when bio-signals indicate optimal engagement.

- **Hybrid EEG–Eye Tracking Interfaces** – Research like *NeuroGaze* (Coutray *et al.*, 2025) combines EEG with eye-tracking to enable hands-free VR interaction [9] [10]. In NeuroGaze, a consumer EEG (Emotiv EPOC X) provides a neural "intent confirmation" signal alongside a Meta Quest Pro's gaze tracker for aiming [9]. Users could select objects in a 360° scene by looking at them and "mentally" confirming (via an EEG-detected pattern). While aimed at control rather than art, it demonstrates multimodal fusion in real time. It also used a **dwell time** gaze paradigm combined with EEG to reduce false activations [11]. *DonutOS Tie-In:* This interface suggests how **Donuscope overlays** might be controlled by gaze in tandem with neural signals – e.g. gaze could initiate a visual transition or bring up a toroidal menu, with EEG confirming intention. It highlights gaze dynamics as a powerful modulator for scene transitions or complexity (preventing the "Midas touch" problem by requiring both steady gaze and mental focus).

- **Oscillatory Phase Alignment and CFC** – Some BCI systems explicitly target neural phase or cross-frequency coupling (CFC) to drive feedback. For instance, **SSVEP-based VR controls** (e.g. Wang *et al.*, 2019) flash visual stimuli at certain frequencies to evoke phase-locked EEG responses for selection tasks [12]. This effectively uses **phase oscillator control**, aligning external flicker with brain rhythms. Additionally, the **TAG Sync** neurofeedback approach trains users to simultaneously raise theta and gamma amplitudes – enhancing theta–gamma CFC linked to insight and fluid intelligence [13] [14]. While these were often audio or simple visual feedback, one can imagine VR scenes that subtly adjust rhythmic visual elements (like pulsating fractal patterns) to entrain or respond to EEG phase. *DonutOS Tie-In:* Phase-locking techniques could inform **Membrane locking** – e.g. once the user's brain oscillations synchronize with a visual pattern (indicating deep engagement), the system "locks" a stable visual configuration (a toroidal pattern stabilizes when phase coherence is detected). It also resonates with DonutOS's focus on phase and cross-band coherence as metrics for **Intention Field** (ensuring the user is in the desired state before advancing complexity).

- **Topological Data & Criticality** – Advanced frameworks are emerging to analyze and drive experiences using complexity science. For example, Fraunhofer's Brainpatterns project (below) applied **topological data analysis** by embedding EEG features in high-dimensional spaces to find clustering patterns corresponding to mental states [15]. This kind of analysis could allow a system to identify when a user's neurodynamics approach an *edge-of-criticality* (a highly fluid, learning-ready state) and then adjust stimuli to maintain that poised state. Though largely conceptual at this stage, it aligns with **predictive coding** theory: an optimal VR feedback loop might keep the user between boredom and overload (where prediction error is neither too low nor too high). *DonutOS Tie-In:* These theories could guide the tuning of DonutOS experiences. For instance, **Symmetry Forge** might introduce just enough pattern novelty (chaos) into fractal visuals to push the brain toward criticality, while **Intention Field** monitors for signs (like increased EEG entropy or specific TDA-derived features) that the user is in a maximally plastic attentional state.

Immersive Art Installations and Biofeedback Art

- **"My Virtual Dream" Dome (2013)** – A foundational large-scale installation that turned collective EEG into an immersive art experience [16] [17]. Twenty participants at a time, each wearing a Muse EEG headband, entered an 18m geodesic dome ("dreamery") at Nuit Blanche Toronto. Inside, **360° panoramic visuals and surround sound** responded to the group's brainwaves in real time [16] [17]. Participants first played a **collective neurofeedback game** requiring them to cycle between relaxation (alpha increase) and concentration (beta increase), then transitioned into a "dream" state where their aggregated EEG drove the selection and blending of artistic video snippets and music [18]. The visuals – described as *"dream-like artistic visuals and soundscapes driven by collective brain waves"* [16] – were projected across the dome, and even live musicians improvised along with the brain-driven visuals [17]. Notably, the participants both reacted to and *simultaneously changed* the environment via neurofeedback [17]. *DonutOS Tie-In:* My Virtual Dream demonstrates **Symmetry Forge** at social scale – many minds collectively forging a visual experience. The use of alpha/beta power to navigate "relaxation vs. focus" modes could inform **Intention Field** algorithms for group coherence. Also, its dome projection parallels how **Donuscope overlays** might envelop a user's view with EEG-guided content. This early project validates that even simple spectral features can drive compelling feedback visuals for large groups.

- **Brain Light Project (2015)** – An interactive light sculpture by artist Laura Jade that "feeds on your thoughts" [19]. This boulder-sized perspex brain sculpture is engraved with neuron-like patterns and equipped with LEDs and speakers. As visitors don a wireless EEG headset, the sculpture visualizes their brain activity: **alpha waves modulate calming blue glows, theta affects focus of light, beta adds frenetic flicker**, etc. [20]. The system creates a **closed-loop**: seeing one's brainwaves externalized in pulsating colored light and ambient sound in turn influences the brainwaves, which is again reflected in the sculpture [20]. Jade describes it as "a constantly changing biofeedback loop that evolves in union with your perception of the artwork" [21]. The piece was developed with a neuroscientist (Peter Simpson-Young) and programmer, merging art and science. *DonutOS Tie-In:* Brain Light shows how **Membrane locking** might look in a visual medium – when a participant achieves a meditative alpha state, the sculpture settles into a symmetric, calm glow (a locked "membrane" of light). Its representation of multiple frequency bands could inspire **Donuscope overlays** that indicate the user's brain state (e.g. a halo overlay that shifts color/geometry with alpha, theta, beta activity). It's a strong example of EEG-driven symmetry, as the illuminated neural network patterns echo the user's internal rhythms.

- **Lisa Park's "Eunoia" (2013–2015)** – A series of performance installations where EEG data from the artist's emotional states were turned into physical vibrations. Park wore a Neurosky or Emotiv EEG headset and routed certain emotional EEG metrics (frustration, meditation, etc.) to drive sine-wave generators that vibrated pools of water. In **Eunoia II**, 48 water dishes responded to different emotion-frequency bands, creating living cymatic patterns on the water surfaces [22]. Strong emotional arousal would agitate the water (chaotic ripples), while calm focus produced gentle symmetric waveforms. By visually "externalizing" her mind's vibrations, Park aimed to *"reflect the vibrations of the mind"* [23] and achieve harmony. This is an early artistic biofeedback that, while largely audio-driven (sound -> water), demonstrates multimodal mapping (brain -> sound -> visual pattern). *DonutOS Tie-In:* Eunoia's translation of EEG to resonant patterns can inform **Symmetry Forge** in DonutOS. It literally forges symmetric geometric patterns (standing waves) based on inner state. Also, its focus on emotional self-regulation through feedback resonates with **Intention Field** – the system would know the user is internally calm when it "sees" stable water mandalas, analogous to a stable toroidal attention field.

- **NeuroCosm (2025)** – A modern immersive art installation by Alma Digital Studio blending EEG, heart biofeedback, generative art and music [24]. Premiered in Washington D.C., Neurocosm invites one user at a time to practice mindfulness while wearing an EEG headset and heart-rate sensor. **Neural activity and HR are captured to control generative visuals and meditative sound in real time** [25]. The generative visuals are often cosmic or geometric patterns ("visual fields") that evolve based on the user's brain-state coherence and heart rhythm. AI algorithms process the biosignals to create an *"audiovisual journey"* unique to the meditator [25]. The goal is an introspective tour of one's mind – as the user becomes more calm and focused, the visuals might increase in symmetry or clarity, and the music shifts toward harmony. *DonutOS Tie-In:* NeuroCosm is directly applicable to **Symmetry Forge** and **Intention Field**. Its use of both brain and heart coherence to modulate visual *coherence* could guide DonutOS's **Membrane locking** criteria (e.g. only when EEG and HRV indicate a stable meditative state does the system "lock in" a high-symmetry fractal scene). Additionally, combining HRV (a measure of autonomic balance) with EEG can enrich the Intention Field model of user state (since DonutOS aims for whole-body measures of attention/relaxation).

- **Brainpalace & Brainpatterns (2020–2021)** – An art–science collaboration (Fraunhofer IAO/ITWM with artist Tatjana Busch) exploring **collective EEG neurofeedback** in an installation setting [26]. The Brainpalace project built a sculptural light/sound environment designed to be **controlled by the brain activities of a group of viewers** [27]. Viewers' EEG signals (features like synchrony or spectral power) were used as control variables to modulate the installation's light patterns in real time [27]. The aim was to foster empathy and social cohesion by literally synchronizing participants' brains via shared feedback visuals [28] [29]. In the follow-up Brainpatterns, the team developed software to detect emerging **patterns in the real-time visualizations** that might correspond to different *levels of consciousness* among the group [30] [31]. They even repurposed algorithms from neonatal brain monitoring – embedding EEG data from multiple people into a 3D space to identify clustering of mental states [15]. This hybrid of art and analytics is pushing the envelope of neurofeedback installations. *DonutOS Tie-In:* Brainpalace shows how **Intention Field** could be scaled to multi-user or social VR: a shared "field" of collective coherence. For example, DonutOS's **Membrane locking** might require multiple users to all reach a phase-lock or shared HRV rhythm to trigger a group-level visual event (just as Brainpalace required group EEG synch for certain light patterns). The project's use of pattern recognition on EEG visuals also aligns with employing **Topological Data Analysis (TDA)** or machine learning to inform DonutOS overlays – e.g. detecting when a user's attention enters a certain "topological cluster" (mind-wandering vs. flow) and adjusting the environment accordingly.

- **SoundSelf (2020)** – An off-the-shelf **immersive audio-visual biofeedback game** (available on PC/VR) that, while not using EEG, is worth noting for its modality and visuals. SoundSelf uses the player's *voice* as the input: the microphone captures the tone and intensity of your sustained chant or humming, and a game engine transforms it into mesmerizing procedural graphics and sounds. Players wear a VR headset (or look at a screen) and vocalize – their voice creates swirling mandala-like fractal graphics and drone-like music that instantly respond to pitch and volume. Louder or higher-pitched tones might brighten the visuals or increase geometric complexity, while steady, calm tones produce stable symmetrical patterns. This induces a trance or meditation state through a loop of vocalization and visual feedback. *DonutOS Tie-In:* Although SoundSelf uses voice instead of EEG, it exemplifies **closed-loop audiovisual synthesis** with a **fractal aesthetic**. The dynamic mandalas and tunnels (often resembling kaleidoscopic tilings) show how **Symmetry Forge** could generate real-time graphics. SoundSelf also touches on **predictive coding** – as users learn the mapping, they intuitively "play" the visuals with their voice, creating a tight perception-action loop. In DonutOS, one could imagine additional biosignals (breath, GSR) augmenting such voice-driven fractals (e.g. a gentle exhale could soften colors or expand a torus). It also demonstrates a commercially accessible toolkit (Unity-based, with some source code available via modding communities) that could be extended with EEG/HRV inputs.

Commercial and Open-Source Platforms

- **OpenBCI Galea (2023)** – A state-of-the-art mixed reality biosensing hardware platform. Galea is a research-grade VR/AR headset attachment co-developed by OpenBCI and Varjo, integrating **multiple sensors**: 10-channel EEG (dry electrodes), 4-channel EMG, 2-channel EOG (eye electrooculography), 1-channel EDA (galvanic skin), PPG for heart rate, and integrated **pupil-based eye tracking** [32] [33]. Essentially, it's a "brain-body data" headset that can feed all these signals into game engines (Unity/Unreal) in real time. This opens the door for truly multimodal feedback experiences – a developer can access the user's brainwaves, facial muscle activity, eye gaze, sweat level, and pulse simultaneously and program the virtual environment to respond. *Example:* A relaxation app could decrease VR scene complexity when EMG (frown) and EDA (stress) rise, or a game could detect a user "blinking out" (eyes closed + alpha waves spike) and spawn surprising events to re-engage them. Galea is currently in beta, with an SDK and example projects provided. *DonutOS Tie-In:* Galea directly enables many **DonutOS components** – it's practically a **Donuscope hardware**. With Galea, DonutOS's Symmetry Forge could use real EEG frequencies, Donuscope overlays could leverage eye tracking and EOG for intent, Intention Field gets rich HRV/GSR for emotional context, and Membrane locking can use EMG (stillness) or EDA (calm) as additional locks. Galea is not open-source hardware, but its APIs are accessible (C++, Python, Unity), making it a prime toolkit for implementing DonutOS concepts.

- **Looxid EEG/Eye Headsets (2018)** – Looxid Labs developed an all-in-one mobile VR headset (and later a Vive add-on) with **built-in EEG and eye-tracking**. The LooxidVR device had 6 EEG sensors embedded around the face and two cameras for eye gaze, allowing synchronized recording of brain activity and gaze direction in VR [34]. It was used in studies on VR education, emotion assessment, and even attention training. While primarily a research device, Looxid demonstrated *emotion-adaptive VR*: their demos showed virtual scenes changing color or content based on the user's detected emotional state (using machine-learning on EEG+gaze) [35]. For example, a *"VR classroom"* study used Looxid to measure student engagement; if EEG attention dropped, the system could introduce interactive elements to recapture focus [36]. Looxid's software (Looxid Link/Pro) made it relatively easy to integrate brain/gaze data into Unity3D projects. *DonutOS Tie-In:* This is a precursor to DonutOS's **Donuscope overlays** – it elegantly combines where you look and what your brain is doing. In DonutOS, a Looxid-like system could allow *gaze-contingent neurofeedback*: e.g. a Penrose tiling on the periphery that only becomes orderly when you look at it *and* maintain a certain brainwave pattern. LooxidVR also highlights the importance of data synchronization (their SDK ensured EEG and eye data were time-aligned), which is critical for any closed-loop system to maintain a tight feedback loop.

- **Neurable and Other EEG-VR Interfaces** – Neurable (a Boston-based startup) gained fame by unveiling the *"first mind-controlled VR game"* in 2017. They modified an HTC Vive with 7 EEG electrodes and used machine learning to detect P300 signals, allowing the wearer to select and telekinetically lift objects in a virtual game **using attention alone** [37]. This was more a control mechanism than a continuously modulated environment, but it proved that consumer EEG in VR can be fast and accurate enough for real-time interaction. Neurable released an SDK for Unity, and it inspired other commercial efforts in **neurally-modulated gaming**. Similarly, platforms like *EmotivXR* extend Emotiv's wireless EEG headsets for use in XR, offering Unity plugins to map EEG metrics (like "engagement" or "relaxation" scores) to game parameters. **OpenViBE** (open-source) and **BCI2000** are software frameworks that, while older, have been used to create neurofeedback games and could be interfaced with VR engines for custom projects. *DonutOS Tie-In:* These tools provide the building blocks to realize DonutOS modules. For instance, using Neurable's approach, DonutOS's **Intention Field** could detect a conscious intent (like focusing on a specific fractal node) and then trigger **Symmetry Forge** to reconfigure that part of the geometry. Emotiv's affective measures could drive **Membrane locking** thresholds (e.g. require a sustained "calm" score of X before progressing a level). The existence of Unity SDKs means many of DonutOS's ideas (toroidal attention models, fractal overlays) can be prototyped without reinventing low-level BCI signal processing – developers can plug in these SDKs and focus on content.

- **Biosignals for VR Meditation** – A growing number of wellness VR apps incorporate biofeedback for personalization. **TRIPP** (a popular VR meditation platform) has experimented with integrating users' breathing or heart rate data to adjust meditation scenes (for example, syncing floating particles to the user's inhale-exhale cycle). **DEEP VR** (by Owen Harris, 2016–present) is a notable example: a meditative underwater game entirely controlled by diaphragmatic breathing. The player wears a custom belt or uses a VR controller on the belly to measure breath depth [38]. **Inhale** and you rise through the ocean, exhale to gently sink – your breath literally navigates the 3D world [38]. Meanwhile, the marine environment responds organically: *"When you breathe, the world flows with you. The creatures, plants and patterns sync with your breathing, reinforcing the link between your body and mental state."* [38]. Studies showed DEEP reduces anxiety and increases self-efficacy in players, thanks to this empowering biofeedback loop. Another app, *Flowborne*, similarly uses breath to move through abstract landscapes, teaching slow breathing for stress relief [39]. There are also heart-rate-driven experiences: for instance, **Nevermind** (2015) was a horror game that became scarier as your heart rate rose – a biofeedback twist to train emotional regulation under stress. *DonutOS Tie-In:* These applications illustrate how **HRV, breath, and EMG** can shape the rhythm and coherence of an experience. In DonutOS, **Intention Field** isn't just about neural signals – it could incorporate breath coherence or heart rate variability as inputs. For example, **Symmetry Forge** might generate more complex, chaotic fractals when the user's breath is rapid or heart rate high (signaling arousal), and shift to soothing symmetric patterns (like slowly morphing mandalas or toroidal flow fields) when breathing deepens and HRV increases (signaling relaxation and coherence). **Membrane locking** could require both brain and body agreement – e.g. a stable alpha rhythm *and* a steady 6-breaths-per-minute pattern before "locking" a transcendent scene. Commercial tools to do this are available: off-the-shelf Bluetooth HRV sensors (Polar, Garmin, etc.) have SDKs that could feed into a Unity-based DonutOS, and the breathing belts used in DEEP are relatively simple hardware. This means a DonutOS prototype could readily integrate multi-modal biosignals using existing devices.

- **Open-Source Code and Hardware Access** – Many of the systems above have published code or at least detailed methods. For instance, the **FractalBrain** team released a preprint with system schematics [40] and mention using Unity with EEG SDKs – one could likely reach out to the authors for code (or wait for CHI EA 2024 adjunct proceedings). **My Virtual Dream** shared its data publicly [41] and described their custom software, which used OSC to stream Muse EEG into Unity visuals – offering a template for multi-user neurofeedback games. **Brainpatterns** being a Fraunhofer project might not have open code, but their press releases suggest they built on existing machine-learning libraries that could be replicated. On the commercial side, **OpenBCI** is known for open-source approaches: while Galea hardware isn't free, OpenBCI's driver software and data format are open, and their older EEG boards (Ganglion, Cyton) and the new **Ganglion VR** (a 4-channel EEG module for Quest 2) are available for hackers. The community often shares Unity packages for connecting OpenBCI or Muse to VR. In summary, the barrier to entry for DonutOS-like experiments is lowering:

one can mix and match an EEG headset (Muse 2 or OpenBCI), a heart/breath sensor (Polar H10 or a DIY breath belt), and an eye-tracker (Tobii Unity SDK) – and harness frameworks like **BrainFlow**, **LabStreamingLayer (LSL)**, or manufacturer SDKs to gather all signals in sync. With game engines supporting C# and Python, creating a toroidal "Donuscope" that rotates with head gyro, fractal visuals that pulse with your alpha phase, and audio that harmonizes with your heart/breath is an attainable goal.

Mapping to DonutOS Components

Symmetry Forge: The idea of using biosignals to generate or modulate geometric patterns is at the heart of many systems. FractalBrain's EEG-driven fractals [2] and SoundSelf's voice-driven mandalas are direct precedents. These show that fractal, grid, or lattice visuals can be **forged in real-time** from physiological data. For DonutOS, Symmetry Forge could learn from how FractalBrain maps EEG band power to parameters of a fractal shader (e.g. increasing alpha power could deepen the recursion depth or symmetry of a fractal pattern). The Penrose tilings and Voronoi lattices mentioned could similarly take inputs from coherence scores – e.g. a **Voronoi garden** that becomes more orderly (cells aligning, symmetry emerging) as the user's brain-heart coherence increases (as in NeuroCosm's concept) [25]. In group settings, Brainpalace showed that multiple people's EEG can jointly drive a single visual object [42] – imagine Symmetry Forge blending the "attention shapes" of several users on a shared torus. Additionally, fractal or scale-free feedback might itself enhance certain brain states; the use of fractal dimension in neurofeedback games [43] hints that Symmetry Forge could adjust a pattern's fractal dimension to nudge the user toward the desired state (leveraging the brain's affinity for ~1/f patterns).

Donuscope Overlays: Gaze-contingent interaction and HUD-like overlays are well supported by current tech. NeuroGaze proved EEG and gaze together can be viable for selection and could inform an **attentional overlay** – e.g. a donut-shaped reticle that appears where you look, but only "locks on" (perhaps closes the torus) when your EEG indicates focused attention, preventing accidental activations. This addresses the Midas touch issue in eye-based UIs [44]. Another use: using eye vergence or pupillometry as feedback – some VR studies measure cognitive load via pupil dilation and could display a subtle overlay (color tint or pattern density) reflecting that, cueing the user to rest when overloaded [45]. Looxid's integration of eye and emotion data in VR training is a template for Donuscope's context-aware UI that adapts to both where the user is looking and how they're feeling. For instance, Donuscope might overlay a **navigator grid** on the periphery that only becomes detailed (or legible) when the system senses the user is in a receptive mental state (otherwise remaining minimal to avoid distraction). In practice, frameworks like Pupil Labs or Tobii XR SDK can provide gaze vectors, and one can map those to UI layers in Unity easily – the innovation is tying their visibility/behavior to brain and body signals, which our collected examples demonstrate is feasible.

Intention Field: This component – presumably a representation of user's attentive focus or intention – is supported by multi-sensor data fusion as seen in the therapeutic cinema and VR neurofeedback studies. The Intention Field might aggregate metrics like EEG engagement level, heart-rate variability (for emotional calm), breathing rate, and even subtle EMG (to detect fidgeting or tension) into a single **coherence score**. We saw in Xu's adaptive cinema that using *all* these signals in concert led to better emotional outcomes [7] [8]. Similarly, an **attention index** from EEG (as reviewed by Souza 2021 [46]) combined with eye-tracking (detecting mind-wandering by gaze patterns) was proposed to dynamically adapt VR content [47] [48]. DonutOS's Intention Field could leverage such an index to decide when to introduce new stimuli or when to simplify. For example, if EEG alpha and HRV suggest the user is relaxed but eye metrics show erratic saccades (perhaps attentional boredom), the system might gently increase challenge or switch the visual theme to re-engage (preventing drowsiness). Conversely, if the user is hyper-focused (high beta/gamma, steady gaze) perhaps the Intention Field "locks on" to that target and the system resists distractions (akin to a tunnel vision effect – maybe literally narrowing a toroidal view to the point of focus). Essentially, the Intention Field acts as the **adaptive controller**, much like the narrative controller in Xu's work [49], keeping the experience in that sweet spot of engagement by reading the user's moment-to-moment internal state.

Membrane Locking: Many of the cited systems employ a concept of stabilizing or "locking in" an achieved mental state. In neurofeedback, this is when the user hits the target pattern and the feedback reflects success (e.g. the fractal stops changing erratically, or a pleasant sound plays). For DonutOS, Membrane Locking could mean that once the user achieves a certain coherence (perhaps high alpha-theta CFC indicating deep meditative trance, or a specific phase alignment with a visual flicker), the system *locks the current audiovisual configuration* and holds it as long as the state persists. This was hinted at in TAG Sync: after some initial chaotic fluctuations, the neurofeedback sought a *stable increase in cross-frequency coupling* and clinicians observed that once achieved, it corresponded to moments of insight or "aha" [50]. A DonutOS analogy: imagine a swirling toroidal world that the user is trying to mentally stabilize – at first it's noisy, but when they find the right mental rhythm, the torus crystallizes into a stable, symmetric shape. That stability remains (is "membrane-locked") until the user's state deviates, at which point instability (visual distortion) resumes, cueing the user to re-center. This mechanic encourages the user to maintain a target brain-heart state. Some VR meditation apps already do simplified versions – e.g. in DEEP, if your breath becomes shallow, the visuals might dim or wobble, whereas smooth breathing keeps the world serene [38]. Another example: a **phase-lock game** where the background binaural beat or flickering light tries to pull the user's brainwaves to a frequency; when the EEG frequency locks (within a narrow range of the target), the environment could enter a "slow-motion" or highly ordered phase – literally indicating the membrane (boundary between chaos and order) has been crossed. Membrane locking could also involve **topological signals**: as Fraunhofer's project suggested, detecting an emergence of a particular EEG pattern cluster might indicate a qualitative mental shift [31] – DonutOS could then freeze or capture that moment (like taking a snapshot of the Intention Field) so the user can consciously explore it. Hardware-wise, implementing membrane locking might require filtering for specific synchrony (EEG phase coupling detectors as in some BCI, or simply thresholds on multiple signals). But our sources show even simple metrics (alpha up, heart rate down, etc.) can serve as proxy for such locked-in states [8].

In conclusion, the past decade has produced a rich tapestry of **multimodal closed-loop systems** – from academic prototypes to artistic endeavors and commercial kits – all pointing toward experiences that blur the boundary between user and environment. These systems dynamically modulate visual complexity, symmetry, soundscapes, and narrative **in direct response to the user's mind and body**. They leverage EEG rhythms, eye gaze, motion, heart/breath, and muscle signals to create feedback loops that can entertain, heal, and enlighten. By categorizing these efforts (research, art, commercial) and examining their architectures, we gain concrete guidance for designing DonutOS's modules like Symmetry Forge, Donuscope, Intention Field, and Membrane locking. Essentially, DonutOS can stand on the shoulders of these projects: combining **the fractal artistry of neurofeedback VR** [2], **the multi-sensor fusion of affective computing** [7], and **the engagement algorithms of closed-loop games** [5] to build a toroidal, fractal attention playground that adapts to and augments human consciousness in real time. The source code, hardware, and lessons learned from these systems are largely accessible, meaning the vision of DonutOS – an **immersive, bio-responsive OS for the mind** – is increasingly within reach of developers and researchers today.

Sources: Recent peer-reviewed papers, installation reports, and product documentation have been cited to ground each example: academic systems like FractalBrain [2] and closed-loop VR therapy [7]; art installations including My Virtual Dream [16] and Brain Light [20]; and commercial toolkits such as Galea [32] and LooxidVR [51]. These references provide further technical details and outcomes for each project discussed.

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