Breathing Space: Spatial Mapping of Breath and Cardiac Biofeedback for Affective State Representation and Coherence Training in Viscereality

George Fejer*
Cognitive Psychology
Unviersity of Konstanz
Constance, Germany
ALIUS Research Network
Berlin, Germany
george.fejer@uni-konstanz.de

Till Holzapfel
Mesmerprism
Osnabrück, Germany
tillholzapfel@viscereality.org

Taru Hirvonen
Tampere University
Tampere, Finland
2taruhi@gmail.com

Anestis Lalidis Mateo
Hochschule Bielefeld – University of Applied Sciences and Arts, Institute for Building Intelligence, Bielefeld
Bielefeld, Germany
alalidis@hsbi.de

Johannes Blum
Pädagogische Hochschule Schaffhausen, Schaffhausen
Schaffhausen, Switzerland
Johannes.blum@phsh.ch

Michael Gaebler
Department of Neurology, Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig
Berlin, Germany
gaebler@cbs.mpg.de

Bigna Lenggenhager
Association for Independent Research
Zürich, Switzerland
bigna.lenggenhager@gmail.com

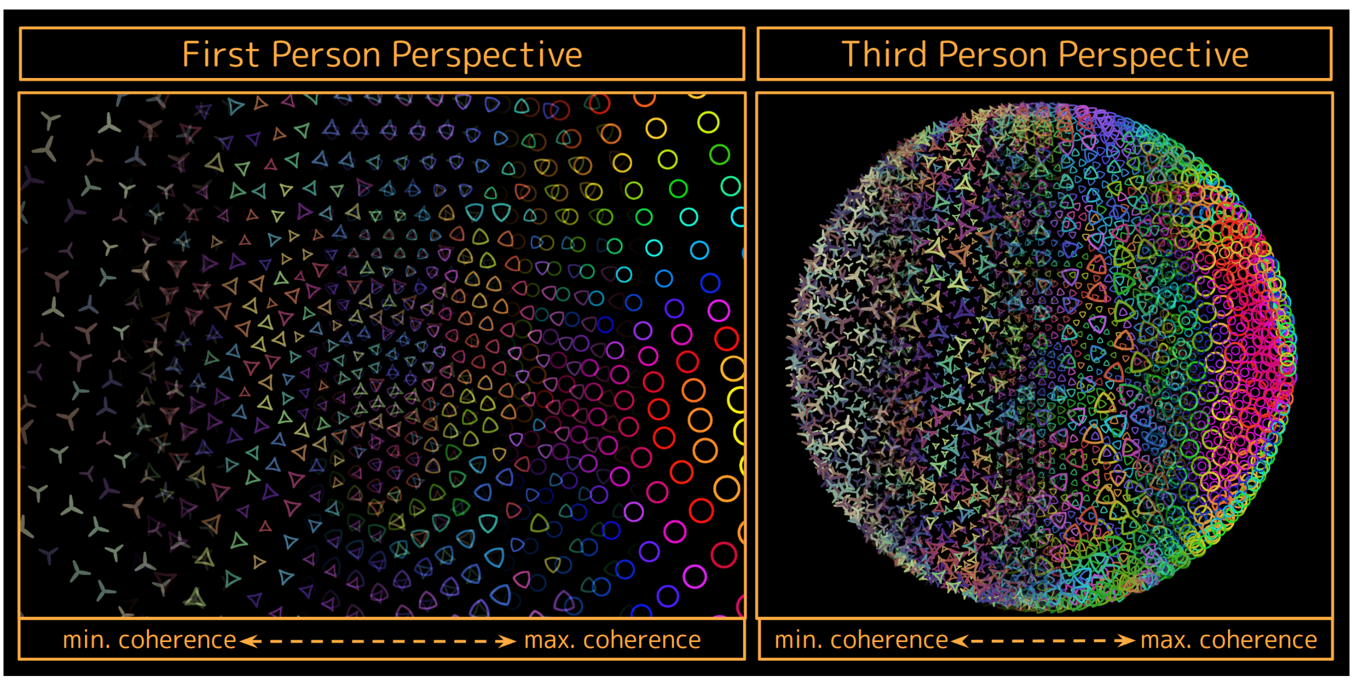

Figure 1: Bioresponsive VR interface for spatial mapping of heart coherence and breathing.

Abstract

Heart rate variability biofeedback has emerged as a validated intervention for stress management and emotional regulation through coherence breathing techniques. Existing biofeedback systems typically present cardiac and respiratory signals as separate feedback channels or rely on discrete interface elements that fragment attention and disrupt immersion. We present a design framework that extends Viscereality, a bioresponsive VR framework originally developed for breath mapping, to integrate multi-channel biofeedback including heart rate within immersive VR, centered on a particle-based environment that functions as a spatial body-mapping interface. By leveraging bioresponsive breath interactions for embodiment and weak representational aesthetics for cardiac coherence, the framework aims to encode both streams within a shared visual substrate, reducing the attentional task-switching and experiential fragmentation that multi-channel displays otherwise risk. The system translates lung volume into spatial expansion and contraction of the environment itself, maps cardiac coherence onto affective visual dimensions (angularity, brightness, saturation, symmetry), and embeds breathing guidance within the same geometric substrate. We present the design rationale and implementation of this framework, with empirical validation of its effectiveness to be conducted in future studies.

CCS Concepts

• **Human-centered computing → Virtual reality**; *Information visualization*; *HCI theory, concepts and models.*

Keywords

heart rate variability, biofeedback, virtual reality, affective state modulation, affective visualization, coherence breathing

ACM Reference Format:

George Fejer, Till Holzapfel, Taru Hirvonen, Anestis Lalidis Mateo, Johannes Blum, Michael Gaebler, and Bigna Lenggenhager. 2026. Breathing Space: Spatial Mapping of Breath and Cardiac Biofeedback for Affective State Representation and Coherence Training in Viscereality. In *1st International Conference on Human-Computer Interaction in the Alps (AlpCHI 2026), March 01–05, 2026, Ascona, Switzerland*. ACM, New York, NY, USA, 8 pages. https://doi.org/10.1145/3780045.3780061

1 Introduction

Immersive technologies offer significant potential for health interventions, and breathing has emerged as a popular and widespread therapeutic modality integrated into various VR systems for promoting mental health [36]. However, recent systematic reviews indicate that VR-based breathing interventions have demonstrated that their effectiveness is on par with non-VR approaches in improving mental health outcomes or physiological stress measures [13], which begs the question: what particular advantage does this technology yield if its effectiveness does not exceed that of traditional protocols? We argue that the value proposition of VR lies in its potential for home-based applications, where its capacity to create engaging, immersive, and aesthetically pleasing experiences could sustain long-term adherence without external supervision. By contrast, clinical biofeedback systems emphasize precise physiological monitoring and validated protocols, achieving therapeutic outcomes in supervised settings where patients are monitored and incentivized to participate [10]. This reflects a key gap in expertise: clinical developers excel at validated protocols with precise physiological monitoring, while entertainment developers excel at crafting intrinsically rewarding experiences that sustain voluntary participation.

To bridge this gap, we present a system that integrates heart and breath rate data into aesthetically compelling, non-intrusive feedback while supporting validated protocols for evaluating efficacy within established frameworks for heart rate variability training and stress reduction. Building on immersive applications that use breath-based interactions to expand awareness of breathing [39] through interoceptive-exteroceptive sensory substitution [20, 57], where the expansion and contraction of lung volume is intuitively mapped onto the expansion and contraction of virtual space. This approach was recently extended through a dynamic breath-responsive particle orb [15], whereby the spatial properties of the surrounding environment are represented via a bioresponsive particle field that reacts to the user's breath. Building on this framework, we designed a particle field to provide cardiac feedback through continuous aesthetic mappings of angularity, brightness, saturation, and symmetry. Informed by literature on affective visualization in VR [38] and implementations for non-intrusive affective feedback [17], we employ weakly representational aesthetics [18] where abstract geometric properties translate valence states associated with heart rate variability into continuous visual transformations without relying on fixed metaphors or gamified point systems. Moreover, breathing guidance is embedded as a pacer that provides performance monitoring, indicating whether users should adjust their pace relative to their optimal heart rate variability. All three feedback channels (embodied breath-driven expansion, affective cardiac feedback, and performance monitoring) are integrated non-intrusively into the same visual substrate. An overview is shown in Figure 1, with an animated video available in supplementary materials. VR is essential because breath-driven spatial expansion creates embodied sensorimotor coupling absent in 2D observation. Designed as an experiential container for guided breathwork rather than a task-oriented interface, weak representational aesthetics guide users naturally toward coherent states through perceptually fluent changes, minimizing explicit instruction. A demonstration video showing user engagement with a previous breath-only version of the Viscereality system [15], which follows the same fundamental interaction approach, is available at osf.io/4enfg; supplementary materials for the present work, including animated videos S1–S7 and a demo, are available at osf.io/f2gmw.

*Corresponding author.

ACM ISBN 979-8-4007-1948-6/26/03
https://doi.org/10.1145/3780045.3780061

2 Biomedical Foundations of Heart Rate Variability Biofeedback

Heart rate variability (HRV) reflects natural fluctuations in interbeat intervals that indicate dynamic autonomic nervous system regulation, with higher variability associated with greater cardiovascular health, emotional resilience, and stress adaptability. The key mechanism underlying HRV biofeedback is respiratory sinus arrhythmia (RSA), where breathing naturally modulates heart rate through vagal influences. When breathing is slowed to approximately 0.1 Hz (six breaths per minute), these cardiac oscillations enter into resonance with baroreflex dynamics, producing smooth, sinusoidal heart rate patterns termed "cardiac coherence" that reflect optimal autonomic efficiency. This coherence metric proves particularly valuable for biofeedback systems because it responds more sensitively to breathing changes than other heart rate measurements, making it an effective real-time indicator of physiological state [42]. Cardiac coherence also reflects affective experience, with coherent patterns often accompanying calm and positive states while incoherent patterns are linked to stress and negative affect. This physiological-emotional coupling provides a rationale for using affective feedback to guide users toward a high-coherence, high-valence embodied state space.

Individual resonance frequencies vary between 4.5-6.5 breaths per minute based on cardiovascular anatomy. While guidelines exist for determining individual coherence frequencies [43, 49], a systematic review of 143 HRV biofeedback studies revealed divergent implementation approaches [25]: one third instruct all participants to breathe at a fixed rate of six breaths per minute, one third identify individual coherence frequencies, and one third additionally provide real-time heart rate displays for self-adjustment. Critically, two-thirds of HRV biofeedback studies lack real-time performance monitoring, providing no mechanism for users to adjust their breathing based on feedback.

Breathing visualizations generally fall into pacer-only or tracker-only approaches. Pacer-only designs provide rhythm cues but no feedback on synchronization quality [11], while tracker-only systems visualize measured respiration without pacing targets [7, 8]. Dual-channel systems typically present pacer and measured data as separate elements [29, 51], forcing users to mentally compare the two. Mindfulness-oriented VR applications sometimes combine a central breathing sphere pacer with a surrounding tracker ring, using global scene desaturation to indicate misalignment. However, such global feedback is incompatible with systems where scene dynamics already encode another biosignal. In our case, cardiac coherence drives global brightness, saturation, and symmetry, necessitating local mismatch visualization within the same geometric region as the pacer and tracker rather than global environmental changes.

These biomedical insights translate into two design requirements. First, the interface must integrate performance monitoring that verifies breathing pace and provides real-time coherence reflection rather than relying solely on fixed pacing cues. Second, the system must implement adaptive control, continuously comparing coherence outcomes against HRV metrics and guiding users to adjust their breathing cycles until their individual resonance frequency is approached. Building on prior adaptive strategies such as ViBreathe [58], which demonstrated how dynamically adjusting feedback can improve performance and reduce fatigue, our design ensures users are steered toward physiologically optimal breathing patterns in an unobtrusive and embodied manner tailored to immersive VR.

3 Affective Affordances of Representational Aesthetics in HRV Biofeedback Interfaces

Affective affordances refer to the possibilities a visualization offers for mapping affective dimensions onto physiological feedback. Following the representational continuum of structural specificity and symbolic rigidity [18], we distinguish between strong and weak representations. At the strong end, precise symbols and explicit metrics constrain interpretation; at the weak end, minimal structure enlarges the space of plausible meanings while increasing the risk of ambiguity.

Strong, data-forward interfaces present heart activity as tachograms, spectrograms, or parametric summaries, paired with breathing pacers and color-coded indicators. They support precise learning but offer limited affective interpretation. This includes multimodal systems using haptics for breath pacing [9], where gains remain directed toward precision rather than aesthetic affordances.

Gamified approaches differ in how representational affordances are realized. FitLab Game maps HRV metrics onto character movement, supporting skill acquisition but limiting affordances to performance [14]. The horror game Nevermind takes a more open-ended approach, where elevated heart rate intensifies disturbing imagery, expanding affordances toward affective modulation [31]. Board-game implementations extend this further by embedding HRV feedback into multiplayer mechanics [55].

Metaphorical mappings transform abstract physiological data into familiar imagery. StressTree maps coherence onto tree vitality [59], Heart Garden translates it into garden flourishing with clearing skies and opening flowers [40], and Blum et al. [6] used a beach scene where coherence brightened or dimmed the atmosphere. These designs reframe numerical signals as intuitive, personally meaningful states through representational metaphors.

The weakest representation is exemplified by George Khut's Cardiomorphologies [35], an artwork visualizing real-time heart and breath through projected visuals and sound. Rather than conveying data precisely, the strategy emphasizes aesthetic richness and ambiguity. Participants expecting control reported frustration, while those adopting an exploratory stance found the ambiguity absorbing, demonstrating how weak representationalism expands affordances through contemplation rather than challenge.

Our design argues for a middle ground. Therapeutic applications require sufficient clarity to orient users toward health outcomes, yet weak representational approaches demonstrate the value of ambiguity for sustaining curiosity-driven engagement. We seek to reconcile these demands by embedding biomedical targets within aesthetic mappings open-ended enough to invite exploration, yet structured enough to guide users toward therapeutic goals.

4 Affective Mappings of Cardiac Coherence

In natural environments, sensory features co-occur in reliable patterns: brightness signals openness, warmth, and visibility; darkness implies concealment or threat; vivid saturation signals ripeness, while desaturation cues decay. These regularities are internalized as

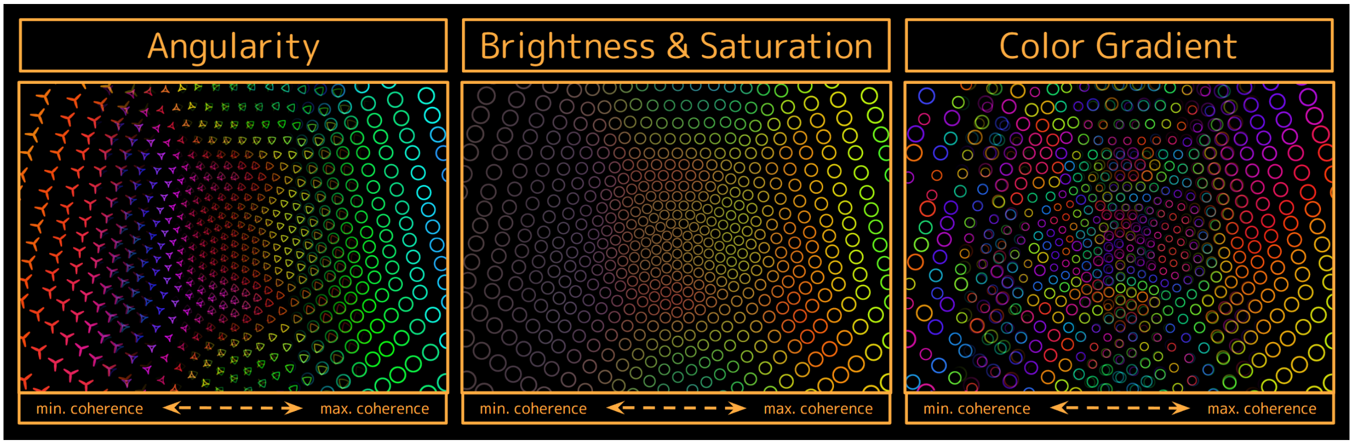

Figure 2: Crossmodal affective mappings used in our system. From left to right: angularity decreases toward rounded shapes; brightness and saturation increase; and a coherence-driven color gradient emerges. The left edges depict low coherence and the right edges high coherence.

implicit associations, and termed as crossmodal correspondences, often manifesting seemingly arbitrary associations such as the infamous kiki-bouba effect: when presented with a jagged shape and a rounded one, people across cultures almost always pair the jagged form with "kiki" and the rounded form with "bouba." This shows that basic perceptual features are systematically linked to sound and affect, with sharp angles implicitly evoking threat or negativity and smooth pleasantness. Because these mappings operate automatically, they provide reliable design primitives for conveying perceptual or affective states. Notable implementations of this include, the TimToShape music visualizer which employs crossmodal correspondences for intuitive visualization of timbre through visual shapes [2]. Other domains also encompass the design of user interfaces that rely on touch, smell or taste, as demonstrated by the study of auditory seasoning filters [24], that can enhance the tastiness of chips by increasing the sound of their crispiness (among other qualities). In our design, we aim to implement affective–visual correspondences that can be mapped and modulated along a continuous 0–1 scale. These features are modulated by the cardiac coherence metric, which fluctuates between 0 and 1 to track the user's physiological performance during slow breathing, with the aim of guiding the user into a positive affective state space, with the positive end of the continuum designed to motivate users to regulate their cardiac coherence breathing and reach more positively valenced state-space. For our design, we designated four visual primitives to visually map affective valence: angularity, brightness, saturation, and pattern symmetry.

4.1 Angularity vs. Roundness

Human beings preference for roundness over angularity is one of the most well-researched correspondences, that is shown to be both neurobiologically grounded [4] and cross-culturally reliable [12, 19]. Simple geometric forms carries valence, as shown by implicit measures angular, downward-pointing forms (acute "V"s) are implicitly tagged as negative or threatening, while curvilinear shapes (circles, rounded contours) are tagged as pleasant [26] indicating that shape-to-valence mappings operate automatically and can serve as reliable design primitives for affective feedback. This universal aversion extends to applications in disparate fields such as nuclear semiotics[23], where proposed spike fields rely on angular geometry's stable threat associations to warn future generations of nuclear waste deposit sites [54]. And it has also been successfully tested in the domain of tangibles in human-computer interaction design [48], as it was shown that sharp, angular, and stiff forms are reliably associated with unpleasant or threatening affective states, while rounded and softer forms are associated with pleasant and calming states[48]. In our design we incorporate the dynamic transition between an angular star and fully rounded circle as a visual affective mapping of the cardiac coherence. As shown in Figure 2, the transition from angular to rounded shapes conveys changes in cardiac coherence. An animated video of this figure is available in the supplementary materials.

4.2 Brightness and saturation

Brightness and saturation also present reliable indicators of valence, whereas color by comparison yields far more ambiguous results depending on context. For instance, preference of color hues seem to depend more on the lightness of color [60], and color-pairings seem to vary widely across cultures [28]. Brightness serves as a reliable implicit marker of valence [46, 47], with brighter stimuli consistently associated with positivity in implicit reaction-time measures [46]. This association reflects a positive preference towards brightness that operates at a pre-attentive level, suggesting that luminance carries a positive affective meaning. Next to brightness, saturation also functions as a distinct dimension in affective mapping. Reducing saturation in real-life images consistently lowered pleasure ratings, with more saturated images judged as more pleasant and thus modulating the intensity of affective experience [30]. The effects of brightness and saturation are moreover corroborated by findings showing that in explicit valence ratings of Munsell color patches, where hue was kept constant, higher brightness and higher saturation were consistently judged as more positive [45]. Based on these findings we implement a brightness saturation gradient mapped onto low and high cardiac coherence. This effect is illustrated in Figure 2, where increases in brightness and saturation correspond to higher coherence. An animated video of this figure is available in the supplementary materials.

4.3 Pattern Symmetry

We include symmetry as an aesthetic dimension because validated findings link it to positive affect, with important caveats. Symmetry has been proposed as an aesthetic primitive whose appeal reflects how the visual system processes regularity [32]. Explicit judgments can diverge, however: art experts often prefer asymmetry, underscoring the influence of expertise, cultural learning, and context [5, 27]. Beyond bilateral forms, fractal structures that instantiate degrees of self similarity are widespread in nature and appear in abstract art, including Jackson Pollock's abstract drip art paintings [52, 53], which predate the formal mathematical description of fractals. Building on this, emerging work is examining how organized complexity shape aesthetic preference [1]. And despite incomplete consensus, we include symmetry because immersive VR enables a novel tool: studying dynamic structural patterns unfolding over time within an embodied spatial environment, rather than judgments of static images. This shifts focus toward aesthetic feelings as precursors to judgment [37], aligning with neuroaesthetic emphasis on experience arising from object-individual-context interplay[41]. On this basis we treat the symmetry to asymmetry gradient as an exploratory axis for aesthetic modulation, and following Fejer et al. [15] we implement a coupling kernel in a Kuramoto oscillator field to support synchronization of patterns that emerge through dynamic motion, yielding coherent symmetric motifs or more irregular configurations as a function of coupling. As illustrated in Figure 2, higher coherence yields globally symmetric patterns in the animation cycle of the particle color, whereas lower coherence produces irregular configurations of color. An animated video of this figure is available in the supplementary materials.

5 Technical Implementation

5.1 Geodesic Particle Neighborhoods

We adapted the particle setup from our previous Viscereality [15] system, implementing an icosphere generated by repeatedly subdividing a regular icosahedron and projecting the new points onto a sphere. This produces an almost even distribution of vertices: most have six neighbors (hexagons) and twelve special points have five neighbors (pentagons). Each vertex holds one particle and a simple phase oscillator. The entire particle field expands and contracts in synchrony with the user's lung volume, so that breathing directly drives dynamic interactions with the environment and simultaneously provides feedback of diaphragmatic breathing. We further extend the original implementation in three ways: (1) two neighbor rings (immediate and secondary) control short- vs. medium-range coupling; (2) coupling strength changes with sphere radius so that coherence is strongest at full inhale/exhale and loosens near the midpoint; and (3) a custom shader pipeline separates global coherence effects from the local pacer–tracker animation, while rendering everything as a unified particle field. This geodesic layout ensures efficient updates and supports smooth, symmetric patterns without visible mesh artifacts.

5.2 Physiological Signal Acquisition and Adaptive Pacer Optimization

To capture cardiovascular data without tethered hardware, the system integrates a Polar H10 chest strap directly with the Meta Quest 3 headset over Bluetooth Low Energy (BLE), adapted from existing repositories [6, 33]. The Unity application decodes interbeat intervals (IBIs) with artifact detection and sliding-window buffering to maintain signal integrity. Coherence is computed in real time as the ratio of narrowband power around the dominant low-frequency peak to total spectral power, following established protocols [6, 34]. Implementing this pipeline entirely within Unity enables frame-synchronous updates essential for perceptual continuity in VR. Inspired by ViBreathe [58], the system iteratively adjusts the breathing pacer toward each user's resonance frequency, reducing respiratory fatigue associated with fixed-rate pacing. Extended details on artifact filtering, spectral analysis, coherence calculation, and adaptive pacing parameters are provided in the supplementary materials (Section S3.1).

5.3 Shader Design and Particle Control

A custom shader architecture enables two independent animation channels within the unified particle field. The first channel drives coherence-responsive aesthetics (brightness, saturation, angularity, symmetry), while the second supports the breathing pacer-tracker visualization. This separation allows cardiac coherence to modulate global visual dynamics while respiratory guidance operates locally, without fragmenting the system into multiple particle emitters. Visual parameters remain adjustable at runtime, providing a flexible substrate for experimental manipulation of affective mappings. Extended implementation details, including the integration with Unity's Shuriken framework and Job System, are provided in the supplementary materials (Section S3.2).

5.4 Breathing Pacer–Tracker Visualization

Our solution co-locates pacer and tracker within a single pentagon-tiled particle field, leveraging the icosphere geometry that defines the spatial layout. The pacer is encoded as a breathing phase animation across a subset of pentagons, while the tracker reflects the user's measured phase. Phase mismatch is visualized through a color gradient and particle animation changes in the interstitial "gap" between the two, transforming synchronization error into a perceptually compelling stimulus. This approach affords visceral feedback: rather than relying on numerical metrics, it creates an aesthetic "pull" toward synchrony, aligning with research that links color, brightness, and motion fluency to affective valence. Importantly, this visualization is embedded in the same particle substrate that conveys heart-coherence dynamics, maintaining the perception of a single, unified, embodied sphere rather than separate UI layers. This reduces cognitive load by allowing users to perceive guidance and feedback peripherally without splitting attention, supporting immersion and long-term engagement. Curve-based systems remain the most precise means of displaying respiratory timing, but they demand focused attention and can break flow. By

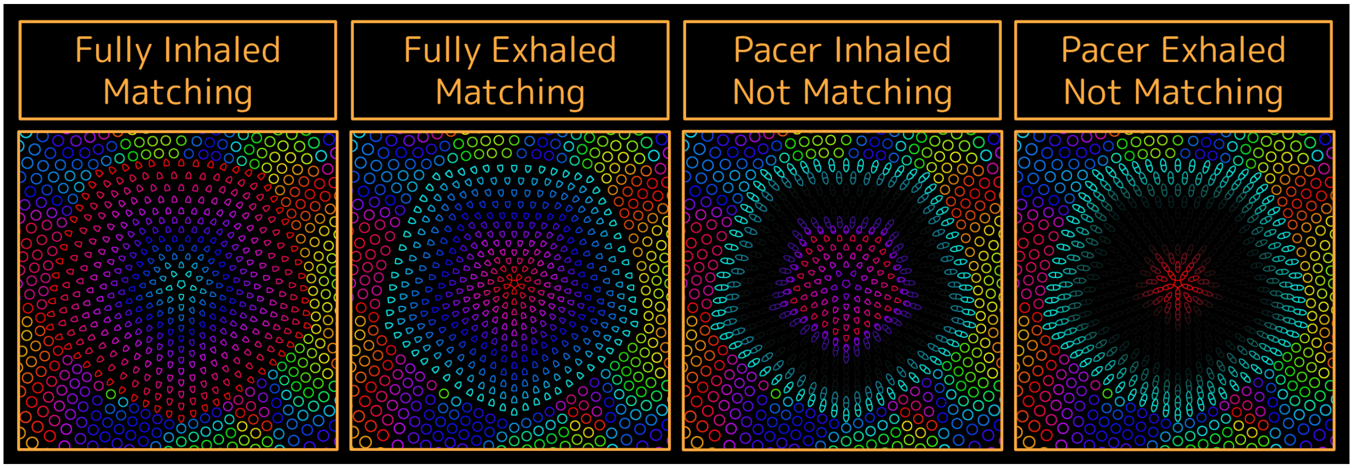

Figure 3: Breathing pacer–tracker visualization states. Left: user fully inhaled and synchronized with the pacer. Second: user fully exhaled and synchronized. Third: pacer inhaled but not matching the user. Fourth: pacer exhaled but not matching the user.

contrast, this particle-based approach is designed for sustained use: it provides sufficient accuracy to guide behavior while preserving aesthetic engagement—crucial for user retention. While this work focuses on the visual channel, the design can be readily extended to auditory and haptic modalities, enabling multimodal reinforcement without compromising coherence. The shader architecture enables this by supporting two independent animation channels per particle set, one for coherence-driven global dynamics and one for pacer–tracker synchronization cues, ensuring a coherent and immersive multimodal feedback environment. The resulting pacer–tracker states are illustrated in Figure 3, which shows synchronized inhalation and exhalation as well as mismatched pacer phases. An animated video of this figure is available in the supplementary materials.

6 Future Evaluation

Future work will systematically evaluate the system's contribution to physiological regulation and subjective experience through a mixed-methods approach. Quantitatively, we will compare three conditions (combined pacer-tracker, pacer-only, no pacer), and the isolated visual features, while measuring coherence metrics (LF/HF ratio, peak power near resonance frequency) alongside embodiment and presence scales to assess whether integrated feedback provides effective entrainment and whether embodiment predicts coherence gains. Qualitatively, semi-structured interviews will probe user perceptions of immersion, motivation, and aesthetic experience to clarify whether mismatch visualization and particle animations function as supportive cues rather than intrusive disruptions. These measures will determine how the system's design elements combine to shape physiological outcomes and experiential quality, informing iterative refinements to maximize coherence enhancement and sustain long-term engagement.

7 Discussion

This work presents a design approach for integrating multiple biofeedback channels into a unified VR environment without disrupting user experience. We demonstrate how heart coherence biofeedback and breathing guidance can be embedded within a single particle-based sphere, allowing users to experience breathing guidance, performance monitoring, and cardiac coherence as facets of the same environment rather than separate interface elements. This spatial integration approach aims to reduce attentional fragmentation while preserving immersion, though thorough user experience evaluation remains necessary to validate these design goals.

Our design complements prior mindfulness-oriented VR work that used global scene desaturation to reflect misalignment. In contrast, we visualize mismatch locally through color gradients and particle animation within the pacer-tracker gap, allowing global dynamics to remain dedicated to coherence-driven modulation. This separation of feedback channels ensures cardiac coherence remains the primary determinant of aesthetic state, while breathing feedback serves as guiding input.

Drawing on neuroaesthetic research into cross-culturally consistent visual-affective correspondences, the interface design aims to transform physiological regulation into an intrinsically rewarding experiences. By mapping coherence to brightness, saturation, angularity, and symmetry, the system is designed to encourage alignment through perceptual fluency rather than explicit scoring or gamification. Whether this approach successfully invites exploration rather than performance-oriented engagement requires empirical investigation through user studies.

The architecture is extensible: auditory and haptic cues can be added without reworking visual logic, and new biosignals can be integrated into the shared data pipeline. Haptic feedback presents a particularly accessible avenue, as the handheld controller already serves as the breathing input device and supports vibrotactile output, enabling differentiated vibration patterns for inhalation versus exhalation with minimal additional complexity. Recent work on resonance frequency breathing found that combining haptic with visual guidance nearly doubled the concentration of HRV power at the resonance frequency compared to visual guidance alone, with participants achieving tighter adherence to target breathing rates [9]. The haptic modality used vibration intensity that increased during inspiration and decreased during expiration, a pattern directly transferable to our controller-based input device.

Further possibilities for multimodal interaction arise from sonification, particularly head-tracked binaural spatial audio rendered via head-related transfer functions (HRTFs), which is now computationally feasible in real-time VR [22, 61] and has been shown to elicit enhanced neural processing compared to diotic sound [21, 50]. The spatial expansion and contraction central to our visual design could be sonified directly: Van Kerrebroeck and Maes [56] demonstrated this using ambisonics, where ambient sounds expanded outward during inhalation and contracted inward during exhalation, producing both the most prominent decrease in respiration rate and the highest pleasantness ratings among tested modalities. Moreover, cardiac coherence could leverage auditory roughness-to-smoothness, a psychoacoustic continuum where rapid amplitude modulation produces harsh sensations associated with negative valence, while smooth, unmodulated tones correspond to positive valence [3, 44]. Notably, Ferri et al. [16] also demonstrated that acoustic valence modulates the multisensory space surrounding the body, suggesting that these sound properties also shape embodied perception of space. It remains an untapped medium in our current design, yet sound's unique capacity to simultaneously encode coherence as valence and breath as spatial extent presents a versatile canvas for exploring how these auditory mappings interact with each other and with their visual counterparts. Future studies will need to assess user retention, perceived agency, coherence outcomes, and the extent to which the design achieves its goal of unifying feedback channels without fragmenting attention and achieving therapeutic efficacy.

8 Conclusion

We introduced a bioresponsive VR interface that unifies cardiac coherence biofeedback and respiratory guidance within a weakly representational particle environment. By spatially integrating a pacer-tracker with coherence-driven aesthetics mapped onto angularity, brightness, saturation, and symmetry, the system reduces attentional fragmentation and aims to make self-regulation intrinsically rewarding. Our Unity-based architecture supports real-time HRV computation from wearable ECG, controller-based breath tracking, and adaptive pacing to converge on each user's resonance frequency. This work bridges clinical precision and immersive design, offering a middle ground between data-forward and abstract artistic approaches. The platform is extensible to additional biosignals and multimodal feedback, positioning it as a testbed for affective, personalized biofeedback in VR.

Acknowledgments

We gratefully acknowledge the financial support of the BIAL Foundation for this research.

References

[1] Mohammad Majid al Rifaie, Anna Ursyn, Robert Zimmer, and Mohammad Ali Javaheri Javid. 2017. On symmetry, aesthetics and quantifying symmetrical complexity. In *International Conference on Evolutionary and Biologically Inspired Music and Art*. Springer, 17–32.

[2] Kota Arai, Yutaro Hirao, Takuji Narumi, Tomohiko Nakamura, Shinnosuke Takamichi, and Shigeo Yoshida. 2023. TimToShape: supporting practice of musical instruments by visualizing timbre with 2D shapes based on crossmodal correspondences. In *Proceedings of the 28th international conference on intelligent user interfaces*. 850–865.

[3] Luc H Arnal, Andreas Kleinschmidt, Laurent Spinelli, Anne-Lise Giraud, and Pierre Mégevand. 2019. The rough sound of salience enhances aversion through neural synchronisation. *Nature Communications* 10 (2019), 3671.

[4] Moshe Bar and Maital Neta. 2007. Visual elements of subjective preference modulate amygdala activation. *Neuropsychologia* 45, 10 (2007), 2191–2200.

[5] Marco Bertamini, Giulia Rampone, Alexis DJ Makin, and Andrew Jessop. 2019. Symmetry preference in shapes, faces, flowers and landscapes. *PeerJ* 7 (2019), e7078.

[6] Johannes Blum, Christoph Rockstroh, and Anja S Göritz. 2019. Heart rate variability biofeedback based on slow-paced breathing with immersive virtual reality nature scenery. *Frontiers in psychology* 10 (2019), 2172.

[7] Johannes Blum, Christoph Rockstroh, and Anja S Göritz. 2020. Development and pilot test of a virtual reality respiratory biofeedback approach. *Applied Psychophysiology and Biofeedback* 45, 3 (2020), 153–163.

[8] Rineke Bossenbroek, Aniek Wols, Joanneke Weerdmeester, Anna Lichtwarck-Aschoff, Isabela Granic, Marieke MJW van Rooij, et al. 2020. Efficacy of a virtual reality biofeedback game (DEEP) to reduce anxiety and disruptive classroom behavior: single-case study. *JMIR mental health* 7, 3 (2020), e16066.

[9] Pierre Bouny, Laurent M Arsac, Antoine Guérin, Guillam Nerincx, and Veronique Deschodt-Arsac. 2023. Guiding breathing at the resonance frequency with haptic sensors potentiates cardiac coherence. *Sensors* 23, 9 (2023), 4494.

[10] Naïg Chenais and Arno Görgen. 2024. Immersive interfaces for clinical applications: current status and future perspective. *Frontiers in neurorobotics* 18 (2024), 1362444.

[11] Luca Chittaro and Riccardo Sioni. 2014. Evaluating mobile apps for breathing training: The effectiveness of visualization. *Computers in Human Behavior* 40 (2014), 56–63.

[12] Erick G Chuquichambi, Oshin Vartanian, Martin Skov, Guido B Corradi, Marcos Nadal, Paul J Silvia, and Enric Munar. 2022. How universal is preference for visual curvature? A systematic review and meta-analysis. *Annals of the New York Academy of Sciences* 1518, 1 (2022), 151–165.

[13] Gabriela Cortez-Vázquez, Marcel Adriaanse, George Louis Burchell, Raymond Ostelo, Georgia Panayiotou, and Elke Vlemincx. 2024. Virtual reality breathing interventions for mental health: a systematic review and meta-analysis of randomized controlled trials. *Applied psychophysiology and biofeedback* 49, 1 (2024), 1–21.

[14] Tony Estrella, Carla Alfonso, Juan Ramos-Castro, Aitor Alsina, and Lluis Capdevila. 2023. A serious game to self-regulate heart rate variability as a technique to manage arousal level through cardiorespiratory biofeedback: development and pilot evaluation study. *JMIR serious games* 11 (2023), e46351.

[15] George Fejer, Till Holzapfel, Andrés Gómez-Emilsson, Taru Hirvonen, Raimonds Jermaks, Johannes Blum, David Lobser, Anestis Lalidis Mateo, David Glowacki, Michael Gaebler, et al. 2025. Viscereality: A Bio-responsive VR System for Breath-Based Interactions and Coupled Oscillator Dynamics to Augment Altered States of Consciousness. In *Mensch und Computer 2025-Workshopband*. Gesellschaft für Informatik eV, 10–18420.

[16] Francesca Ferri, Ana Tajadura-Jiménez, Aleksander Väljamäe, Roberta Vastano, and Marcello Costantini. 2015. Emotion-inducing approaching sounds shape the boundaries of multisensory peripersonal space. *Neuropsychologia* 70 (2015), 468–475.

[17] Antonin Fourcade, Francesca Malandrone, Lucy Roellecke, Anthony Ciston, Jeroen de Mooij, Arno Villringer, Sara Carletto, and Michael Gaebler. 2025. AffectTracker: real-time continuous rating of affective experience in immersive virtual reality. *Frontiers in Virtual Reality* 6 (2025), 1567854.

[18] David R Glowacki. 2024. VR models of death and psychedelics: an aesthetic paradigm for design beyond day-to-day phenomenology. *Frontiers in Virtual Reality* 4 (2024), 1286950.

[19] Gerardo Gómez-Puerto, Jaume Rosselló, Guido Corradi, Cristina Acedo-Carmona, Enric Munar, and Marcos Nadal. 2018. Preference for curved contours across cultures. *Psychology of Aesthetics, Creativity, and the Arts* 12, 4 (2018), 432.

[20] Oran Goral, Iddo Yehoshua Wald, Amber Maimon, Adi Snir, Yulia Golland, Aviva Goral, and Amir Amedi. 2024. Enhancing interoceptive sensibility through exteroceptive–interoceptive sensory substitution. *Scientific Reports* 14, 1 (2024), 14855.

[21] Lizette Heine, Alexandra Corneyllie, Florent Gobert, Jacques Luauté, Mathieu Lavandier, and Fabien Perrin. 2021. Virtually spatialized sounds enhance auditory processing in healthy participants and patients with a disorder of consciousness.

Scientific Reports 11, 1 (2021), 13702.

[22] Kristian JAMBROSIC, Vedran Planinec, and Marko Horvat. 2024. Validation of sound source localization quality in binaural audio synthesis with head-tracking. In *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, Vol. 270. Institute of Noise Control Engineering, 1543–1551.

[23] John Kausch. 2024. Nuclear Semiotics and Knowledge Organization: Five Design Heuristics for Semantic Primitives. In *Knowledge Organization for Resilience in Times of Crisis: Challenges and Opportunities*. Ergon-Verlag, 385–392.

[24] Rebecca Kleinberger, Akito Oshiro Van Troyer, and Qian Janice Wang. 2023. Auditory seasoning filters: Altering food perception via augmented sonic feedback of chewing sounds. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. 1–15.

[25] Jaume F Lalanza, Sonia Lorente, Raimon Bullich, Carlos García, Josep-Maria Losilla, and Lluis Capdevila. 2023. Methods for heart rate variability biofeedback (HRVB): A systematic review and guidelines. *Applied Psychophysiology and Biofeedback* 48, 3 (2023), 275–297.

[26] Christine L Larson, Joel Aronoff, and Elizabeth L Steuer. 2012. Simple geometric shapes are implicitly associated with affective value. *Motivation and Emotion* 36, 3 (2012), 404–413.

[27] Helmut Leder, Pablo PL Tinio, David Brieber, Tonio Kröner, Thomas Jacobsen, and Raphael Rosenberg. 2019. Symmetry is not a universal law of beauty. *Empirical Studies of the Arts* 37, 1 (2019), 104–114.

[28] Harin Lee, Eline Van Geert, Elif Celen, Raja Marjieh, Pol van Rijn, Minsu Park, and Nori Jacoby. 2025. Visual and Auditory Aesthetic Preferences Across Cultures. *arXiv preprint arXiv:2502.14439* (2025).

[29] Paul M Lehrer and Richard Gevirtz. 2014. Heart rate variability biofeedback: how and why does it work? *Frontiers in psychology* 5 (2014), 756.

[30] Chenyang Lin, Sabrina Mottaghi, and Ladan Shams. 2024. The effects of color and saturation on the enjoyment of real-life images. *Psychonomic bulletin & review* 31, 1 (2024), 361–372.

[31] Adam Lobel, Marientina Gotsis, Erin Reynolds, Michael Annetta, Rutger CME Engels, and Isabela Granic. 2016. Designing and utilizing biofeedback games for emotion regulation: The case of nevermind. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*. 1945–1951.

[32] Alexis DJ Makin, Mai Helmy, and Marco Bertamini. 2018. Visual cortex activation predicts visual preference: evidence from Britain and Egypt. *Quarterly Journal of Experimental Psychology* 71, 8 (2018), 1771–1780.

[33] markspan. 2021. *PolarBand2lsl: Send PolarBand H10 Data to an LSL*. https://github.com/markspan/PolarBand2lsl

[34] Rollin McCraty, Mike Atkinson, Dana Tomasino, and Raymond Trevor Bradley. 2009. The coherent heart heart-brain interactions, psychophysiological coherence, and the emergence of system-wide order. *Integral Review: A Transdisciplinary & Transcultural Journal for New Thought, Research, & Praxis* 5, 2 (2009).

[35] Lizzie Muller, Greg Turner, George Khut, and Ernest Edmonds. 2006. Creating affective visualisations for a physiologically interactive artwork. In *Tenth International Conference on Information Visualisation (IV'06)*. IEEE, 651–657.

[36] Elisa Pancini, Anna Flavia Di Natale, and Daniela Villani. 2025. Breathing in virtual reality for promoting mental health: a scoping review. *Virtual Reality* 29, 1 (2025), 29.

[37] Marcus T Pearce, Dahlia W Zaidel, Oshin Vartanian, Martin Skov, Helmut Leder, Anjan Chatterjee, and Marcos Nadal. 2016. Neuroaesthetics: The cognitive neuroscience of aesthetic experience. *Perspectives on psychological science* 11, 2 (2016), 265–279.

[38] Andres Pinilla, Jaime Garcia, William Raffe, Jan-Niklas Voigt-Antons, Robert P Spang, and Sebastian Möller. 2021. Affective visualization in virtual reality: An integrative review. *Frontiers in Virtual Reality* 2 (2021), 630731.

[39] Mirjana Prpa, Ekaterina R Stepanova, Thecla Schiphorst, Bernhard E Riecke, and Philippe Pasquier. 2020. Inhaling and exhaling: How technologies can perceptually extend our breath awareness. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–15.

[40] Chris Rook, Swaroop Panda, Petia Sice, Anne Fenwick, Dan Hodgson, Marianne D Sice, Drummond Owen Heckels, and Garry Elvin. 2025. Heart Garden: Visualizing Heart Rate Data Using the Metaphor of a Garden. *International Journal of Human–Computer Interaction* (2025), 1–17.

[41] Emery Schubert, Adrian C North, and David J Hargreaves. 2016. Aesthetic experience explained by the affect-space framework. *Empirical Musicology Review* 11, 3-4 (2016), 330–345.

[42] Fred Shaffer and Jay P Ginsberg. 2017. An overview of heart rate variability metrics and norms. *Frontiers in public health* 5 (2017), 258.

[43] Fred Shaffer and Zachary M Meehan. 2020. A practical guide to resonance frequency assessment for heart rate variability biofeedback. *Frontiers in Neuroscience* 14 (2020), 570400.

[44] Emily Smit, Andrew J Milne, Roger Dean, and Gabrielle Weidemann. 2019. Perception of affect in unfamiliar musical chords. *PLoS ONE* 14, 6 (2019), e0218570.

[45] Liting Song, Guanghui Zhang, Lan Ma, Johanna Silvennoinen, and Fengyu Cong. 2025. Comparative analysis of color emotional perception in art and non-art university students: hue, saturation, and brightness effects in the Munsell color system. *BMC psychology* 13, 1 (2025), 650.

[46] Eva Specker and Helmut Leder. 2018. Looking on the bright side: Replicating the association between brightness and positivity. *Collabra: Psychology* 4, 1 (2018), 34.

[47] Eva Specker, Helmut Leder, Raphael Rosenberg, Lisa Mira Hegelmaier, Hanna Brinkmann, Jan Mikuni, and Hideaki Kawabata. 2018. The universal and automatic association between brightness and positivity. *Acta Psychologica* 186 (2018), 47–53.

[48] Cameron Steer, Kim Sauvé, Anika Jain, Omosunmisola Lawal, Michael J Proulx, Crescent Jicol, and Jason Alexander. 2024. Squishy, Yet Satisfying: Exploring Deformable Shapes' Cross-Modal Correspondences with Colours and Emotions. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*. 1–20.

[49] Patrick R Steffen, Tara Austin, Andrea DeBarros, and Tracy Brown. 2017. The impact of resonance frequency breathing on measures of heart rate variability, blood pressure, and mood. *Frontiers in public health* 5 (2017), 288289.

[50] Salomé Sudre, Richard Kronland-Martinet, Laetitia Petit, Jocelyn Rozé, Sølvi Ystad, and Mitsuko Aramaki. 2024. A new perspective on binaural beats: Investigating the effects of spatially moving sounds on human mental states. *PloS one* 19, 7 (2024), e0306427.

[51] Aaron Tabor, Scott Bateman, Erik J Scheme, and MC Schraefel. 2022. Comparing heart rate variability biofeedback and simple paced breathing to inform the design of guided breathing technologies. *Frontiers in Computer Science* 4 (2022), 926649.

[52] Richard P Taylor, Adam P Micolich, and David Jonas. 1999. Fractal analysis of Pollock's drip paintings. *Nature* 399, 6735 (1999), 422–422.

[53] Richard P Taylor, Branka Spehar, Paul Van Donkelaar, and Caroline M Hagerhall. 2011. Perceptual and physiological responses to Jackson Pollock's fractals. *Frontiers in human neuroscience* 5 (2011), 60.

[54] Kathleen Marie Trauth, Stephen C Hora, and Robert V Guzowski. 1993. *Expert judgment on markers to deter inadvertent human intrusion into the Waste Isolation Pilot Plant*. Technical Report. Sandia National Laboratories Albuquerque.

[55] Joseph Tu, Eugene Kukshinov, Reza Hadi Mogavi, Derrick M Wang, and Lennart E Nacke. 2025. Designing Biofeedback Board Games: The Impact of Heart Rate on Player Experience. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems*. 1–21.

[56] Bavo Van Kerrebroeck and Pieter-Jan Maes. 2021. A breathing sonification system to reduce stress during the COVID-19 pandemic. *Frontiers in Psychology* 12 (2021), 623110.

[57] Iddo Yehoshua Wald, Amber Maimon, Lucas Keniger De Andrade Gensas, Noemi Guiot, Meshi Ben Oz, Benjamin W Corn, and Amir Amedi. 2023. Breathing based immersive interactions for enhanced agency and body awareness: a claustrophobia motivated study. In *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems*. 1–7.

[58] Bin Yu, Pengcheng An, Sjoerd Hendriks, Ning Zhang, Loe Feijs, Min Li, and Jun Hu. 2021. ViBreathe: Heart rate variability enhanced respiration training for workaday stress management via an eyes-free tangible interface. *International Journal of Human–Computer Interaction* 37, 16 (2021), 1551–1570.

[59] Bin Yu, Mathias Funk, Jun Hu, and Loe Feijs. 2017. StressTree: A metaphorical visualization for biofeedback-assisted stress management. In *Proceedings of the 2017 conference on designing interactive systems*. 333–337.

[60] Shuxin Yu, Lixia Wang, and Yanhong Yang. 2023. Analyzing and predicting colour preference of colour palettes. *Heliyon* 9, 3 (2023).

[61] Yin Zhu, Qiuqiang Kong, Junjie Shi, Shilei Liu, Xuzhou Ye, Ju-Chiang Wang, Hongming Shan, and Junping Zhang. 2024. End-to-end paired ambisonic-binaural audio rendering. *IEEE/CAA Journal of Automatica Sinica* 11, 2 (2024), 502–513.