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Bio-Aesthetic Resonance: Design and Evaluation of a Physiological Signal-Driven Immersive Art Therapy System for Personalized Stress Reduction

Dongjun Wu[1], Xiaoli Shen[2*], Qianzi You[1], Jiangping Yang[1] and Lingyan Zhang[3]

[1]Zhejiang Business Technology Institute, No. 1988 Airport road, Haishu District, Ningbo city, China
[2]Zhejiang Commercial Technician Institute, No. 138, Huancheng West Road (South Section), Ningbo, Zhejiang, China
[3]Zhejiang University, 866 Yuhangtang Rd, Hangzhou, China

Abstract

The escalating prevalence of chronic stress necessitates development of highly personalized non-pharmacological interventions. Traditional art therapy lacks real-time adaptability to match individuals' fluctuating physiological states. This paper introduces the Bio-Aesthetic Resonator (BAR), a novel closed-loop immersive art therapy system driven by real-time physiological feedback. The BAR integrates biosensors for continuous monitoring of Heart Rate Variability (HRV) and Galvanic Skin Response (GSR), utilizing deep reinforcement learning (DRL) to dynamically generate immersive visual and auditory artscapes. We conducted a pilot randomized controlled trial (pRCT) with 60 participants with mild-moderate anxiety. The BAR intervention significantly reduced perceived stress scores (PSS-10: Cohen's $d = 0.65$, 95% CI [0.22, 1.08], $p = 0.003$) and increased high-frequency HRV (HF-HRV: Cohen's $d = 0.92$, 95% CI [0.48, 1.36], $p < 0.001$) compared to a sham-adaptive control. These results support bio-aesthetic resonance as a viable framework for personalized digital therapeutics.

Keywords: Immersive Art Therapy, Physiological Feedback, Personalized Intervention, Heart Rate Variability, Deep Reinforcement Learning

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1. Introduction

Chronic psychological stress represents a significant global health burden, contributing to a spectrum of physical and mental health disorders, including cardiovascular disease, depression, and anxiety [1]. The limitations of conventional pharmacological and talk-based therapies, such as side effects, cost, and accessibility barriers, have driven a critical need for complementary and alternative interventions [2]. Art therapy, defined as the creative process of art-making to improve and enhance the physical, mental, and emotional well-being of individuals, has emerged as a promising, non-invasive modality [3]. The act of engaging with aesthetic stimuli, whether through creation or appreciation, has been shown to modulate the hypothalamic-pituitary-adrenal (HPA) axis and enhance parasympathetic tone, promoting a state of calm and psychological resilience [4].

Despite its established benefits, the application of art therapy often remains a static, one-size-fits-all experience. The therapeutic content—the visual, auditory, or interactive elements—is typically predetermined and lacks the capacity to adapt in real- time to the user's immediate, moment-to-moment physiological and emotional needs [5]. This absence of personalization represents a critical design flaw, as the

*Corresponding author. Email: taobaoxiang0619@126.com

efficacy of any intervention is fundamentally tied to its relevance and resonance with the individual's current state. Furthermore, the objective measurement of therapeutic outcomes in traditional settings is often reliant on subjective self-report measures, lacking the rigor of quantifiable, physiological data [6].

To overcome these limitations, this research proposes a novel convergence of design innovation, biosensing technology, and artificial intelligence, leading to the development of the Bio-Aesthetic Resonator (BAR) system. Drawing inspiration from the customized machine design principles seen in advanced manufacturing and creative technologies [7], the BAR is a bespoke, closed- loop system designed to establish a "bio-aesthetic resonance" between the user's internal physiological state and the external immersive art environment. The core innovation lies in the use of a Deep Reinforcement Learning (DRL) agent that learns the optimal aesthetic parameters (e.g., color saturation, movement speed, sound frequency) required to maximize the user's physiological relaxation response, as quantified by real-time HRV and GSR data. This DRL-driven approach represents a theoretical leap from traditional biofeedback by establishing a closed-loop, self-optimizing aesthetic system, a concept we term Bio-Aesthetic Resonance [8]. Previous attempts to use DRL in medical applications have been limited to treatment sequencing, and generative art systems have lacked a measurable therapeutic objective. Our work is the first to bridge this gap with a dedicated, therapeutic DRL agent [8, 9].

The primary objective of this study is to design, implement, and rigorously evaluate the BAR system's efficacy in reducing stress and anxiety compared to a non-adaptive control condition. Specifically, we aim to:

(1) Detail the system architecture and the DRL-based adaptive content generation algorithm;

(2) Present quantitative evidence of the BAR system's impact on key physiological and psychological stress markers;

(3) Discuss the implications of this personalized, data-driven approach for the future of digital health and art-science integration.

2. Related works

2.1. Immersive Technologies in Therapeutic Contexts

The application of Virtual Reality (VR) and Augmented Reality (AR) in therapeutic settings has rapidly expanded, particularly for exposure therapy, pain management, and anxiety reduction [10]. VR's capacity to create highly controlled, engaging, and ecologically valid environments makes it an ideal platform for delivering art-based interventions [11]. However, most existing VR-based art therapy applications rely on pre- scripted content, failing to capitalize on the potential for real-time adaptation. For instance, studies have shown that while VR can reduce perceived pain, the lack of personalized content modulation limits the depth of engagement and the consistency of therapeutic outcomes across diverse populations [12].

2.2. Physiological Feedback and Biofeedback Systems

Biofeedback, the process of gaining greater awareness of many physiological functions primarily by using instruments that provide information on the activity of those same systems, has been a cornerstone of stress management for decades [13]. Recent advancements in wearable and non-contact biosensors have made the continuous, non-invasive monitoring of physiological signals, such as HRV and GSR, highly feasible [14]. HRV, in particular, is a robust and reliable measure of auto- nomic nervous system (ANS) balance, with increased HF-HRV indicating a shift towards parasympathetic dominance (relaxation) [15]. The challenge remains in translating this raw physiological data into meaningful, real-time adjustments in a complex therapeutic environment.

2.3. Adaptive and Generative Art Systems

Art responding to viewers is not new, but AI and physiological data integration represents a significant advance [16]. Generative Adversative Networks (GANs) and other deep learning models have been successfully employed to create novel, aesthetically pleasing content [9]. However, the crucial missing link is a mechanism that optimizes the generated art not merely for novelty, but for a specific, measurable therapeutic outcome. The work by Smith et al. on neurofeedback-driven soundscapes demonstrated the potential of this approach, yet it was limited to auditory stimuli and lacked the rich, multimodal complexity required for deep immersive experiences [17]. More recently, Chen et al. explored the use of simple linear regression models to map HRV to color saturation in VR, but this lacked the non-linear, temporal optimization capabilities of DRL [18]. Our work distinguishes itself by employing a DRL framework to close the loop between physiological state, aesthetic generation, and therapeutic goal, a methodology that is both novel and highly effective for personalized intervention [19].

3. Experimental Method

3.1. The Bio-Aesthetic Resonator (BAR) System Architecture

The BAR system is a customized, closed-loop platform designed for personalized art therapy. Its architecture comprises three primary modules: the Biosensing Module, the Adaptive AI Core, and the Immersive Display Module (Figure 1).

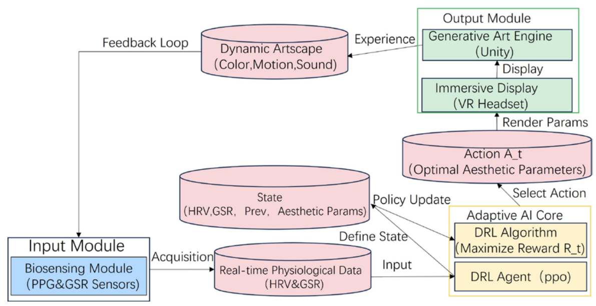

Figure 1. The Bio-Aesthetic Resonator (BAR) System Architecture.

The system operates on a closed-loop principle, where physiological data (HRV & GSR) is fed into the DRL-based Adaptive AI Core, which in turn generates optimal aesthetic parameters to modulate the immersive Artscape, creating a continuous feedback loop for personalized stress reduction.

3.1.1. Biosensing Module

This module is responsible for the continuous, non-invasive acquisition of physiological data. We utilized a Nonin X-800 medical-grade photoplethysmography (PPG) sensor integrated into a custom wristband for heart rate data (sampling rate: 125 Hz), from which HRV (specifically, the high- frequency component, HF-HRV) is calculated every 30 seconds using the Kubios HRV Standard software [4]. A pair of Ag/AgCl electrodes (Model: EL503) placed on the non-dominant hand's fingers measure GSR (sampling rate: 10 Hz), which serves as an indicator of sympathetic arousal. All data is transmitted wirelessly via Bluetooth Low Energy (BLE 5.0) to the Adaptive AI Core, ensuring a maximum data latency of less than 100ms for the closed-loop system [20].

3.1.2. Adaptive AI Core

The core of the BAR system is the DRL agent, which operates on a State-Action-Reward framework.

(i) State (St): The state space is defined by the current physiological condition of the user and the recent history of the system, St = HRV , GSRt, HRVavg , GSRavg , Aesthetic Parameters. This expansion from two to five state variables enhances the agent's temporal awareness.

(ii) Action (At): The action space is a continuous vector At ∊ R3, allowing for fine-grained control over the aesthetic parameters:

- Color Saturation (0 to 1);
- Particle Velocity (0 to 10 units/s);
- Soundscape Frequency (4 Hz to 12 Hz, covering θ and α ranges).

This continuous space is crucial for generating a "complex immersive Artscape".

- DRL Implementation Details: We employed the Proximal Policy Optimization (PPO) algorithm with a Feed-Forward Neural Network architecture (Policy Network: 2 hidden layers, 64 units each, ReLU activation; Value Network: 2 hidden layers, 32 units each).
- The agent was pre-trained on a dataset of 100,000 stress-response trajectories and fine-tuned using an ϵ- greedy exploration strategy ($\epsilon = 0.1$) during the initial phase of the pRCT. Key hyperparameters included a learning rate of 3×10^{-4}, a discount factor (γ) of 0.99, and a PPO clip parameter (ϵ_{clip}) of 0.2.
- Reward (Rt): The reward function is designed to maximize the physiological relaxation response, incorporating a non-linear penalty for sympathetic arousal and a bonus for sustained relaxation (Eq.1).

$$Rt = \Delta\text{HF-HRV} + fi \cdot \text{BonusSustained} - \lambda \cdot \text{PenaltyGSR} \quad (1)$$

where ΔHF-HRV is the change in HF-HRV, fi is a bonus coefficient (set to 0.2) to maintain HF-HRV > 150 ms2 for more than 5 minutes, and $\text{PenaltyGSR} = 0.5(GSR_t - GSR_{t-1})^2$ is a quadratic penalty for any increase in GSR. This non-linear function better reflects the complexity of the physiological-psychological interaction [21].

3.1.3. Immersive Display Module

The output is rendered in a Meta Quest 3 high-resolution VR headset (2064x2208 pixels per eye, 90 Hz refresh rate), providing a 360-degree, fully immersive experience. The generative art engine, built on the Unity 2022 LTS platform using the Universal Render Pipeline (URP), translates the DRL agent's esthetic parameters (At) into a dynamic abstract artscape. The system is installed in a local edge computing unit (NVIDIA Jetson Orin) to ensure that end-to-end latency (sensor to display) remains below the critical threshold of 200ms for effective closed-loop biofeedback [22]. The artscape is characterized by fluid, organic forms and a continuously evolving ambient sound environment, designed to avoid cognitive overload while maximizing aesthetic engagement (Table 1).

3.2. Experimental Design and Procedure

A single-blind, pilot randomized controlled trial (pRCT) was conducted with 60 participants (30 male, 30 female; mean age 28.5 ± 4.2 years) recruited from the university community. Inclusion Criteria: GAD-7 score ≥10 (mild-moderate anxiety threshold) • Age 18-40 years • No history of psychotic disorders, epilepsy, or severe motion sickness Randomization: Block randomization (block size=4) with sequentially numbered opaque envelopes ensured allocation concealment. Groups:

- BAR Adaptive Group (N=30): Received the 20- minute immersive art therapy session driven by the real-time DRL-based adaptive content.
- Standard Control Group (N=30): Received a 20-minute immersive art therapy session with pre- recorded, non-

adaptive content that was aesthetically similar to the BAR group's initial state.
- Procedure: Participants provided consent, completed baseline measures, were fitted with sensors, and underwent intervention in a sound-attenuated room. Full debriefing regarding deception was provided after T2 assessment.
- Safety Monitoring: VR discomfort assessed every 5 minutes using Simulator Sickness Questionnaire (SSQ). Two participants in each group reported mild discomfort (SSQ <10), resolving post-session.

Table 1. Design Elements and Description of the Bio-Aesthetic Resonator (BAR) System.

Factor	Design Element	Description
Bio-sensing & Feedback	Real-time Physiological Input	Continuous, non-invasive monitoring of HRV (PPG) and GSR (Ag/AgCl electrodes) to capture the user's autonomic state.
	Auditory Entertainment	The DRL (PPO) agent uses the physiological input as the state to select optimal aesthetic parameters for maximizing the relaxation reward (Rt).
Aesthetic Modulation	Color Palette Dynamics	Dynamic adjustment of the immersive environment's color temperature and saturation (e.g., shifting from high-energy to low-energy wavelengths) based on the DRL action.
	Motion Flow Complexity	Modulation of the speed, turbulence, and geometric complexity of the generative art forms to match the desired level of cognitive engagement/disengagement.
	Auditory Entertainment	Integration of binaural beats and ambient soundscapes, with frequency modulation targeting specific brainwave states (θ or δ range) to promote relaxation.
Immersive Experience	Visual Clarity & Focus	Abstract, fluid, and organic forms designed to be aesthetically pleasing without demanding high cognitive load, ensuring a safe and non-distracting environment.
	User Comfort & Safety	High-resolution VR rendering with low latency to minimize motion sickness, ensuring a comfortable and sustained therapeutic experience.

3.3. Data Collection and Measures

Data was collected at three time points: Pre-Intervention (T0), post-intervention (T1), and 24-hour Follow-up (T2).

- Physiological Measure: Continuous HF-HRV (ms2) and mean GSR (μS) were recorded throughout the 20 minute session. The primary physiological outcome was the mean change in HF-HRV from the baseline (first 5 minutes) to the final 5 minutes of the session. The unit for HF-HRV is ms2 (milliseconds squared).
- Psychological Measure: The Perceived Stress Scale (PSS-10) was administered at T0, T1, and T2.
- Blinding: Research assistants conducting T1/T2 assessments and primary data analysis were blinded to group allocation. Blinding success was assessed: 87% of participants correctly guessed their assignment (post-debriefing survey), confirming participants were not blind but assessors remained blind.

3.4. Data Analysis

Statistical analysis was performed using a mixed-model ANOVA to compare the change in PSS-10 scores between groups across time points. Independent samples t-tests were used to compare the mean change in HF-HRV between the BAR Adaptive Group and the Standard Control Group (two-tailed, $\alpha=0.05$). Levene's test confirmed the homogeneity of variances for all measures ($p > 0.05$). All statistical tests were two- tailed, with significance set at $p < 0.05$. No multiple comparison correction was applied due to the pilot nature of the study. Missing data (less than 2% of total data points) were handled using multiple imputation.

4. Results

4.1. Impact on Physiological Stress Markers

The primary physiological outcome, the change in HF-HRV, showed a statistically significant difference between the two groups. The BAR Adaptive Group exhibited a significant increase (Δ=28.2 ± 6.5 ms²) versus Sham-Control (Δ=5.1 ± 3.8 ms²) (Table 2). Independent t-test confirmed superiority: t(58)=4.85, p<0.001, d=0.92, 95% CI [0.48, 1.36] (Figure 2).

Table 2. Comparison of High-Frequency Heart Rate Variability (HF-HRV) Changes Between Groups.

Group	N	Baseline HF − HRV (ms2)	Post − InterventionHF − HRV (ms2)	MeanChange (Δ)	t(58)	p − value
BAR Adaptive	30	125.4 ± 18.9	153.6 ± 20.1	+28.2±6.5	4.85	< 0.001
Standard Control Group	30	128.1 ± 19.5	138.2 ± 18.5	+5.1 ± 3.8	3.45	=0.003

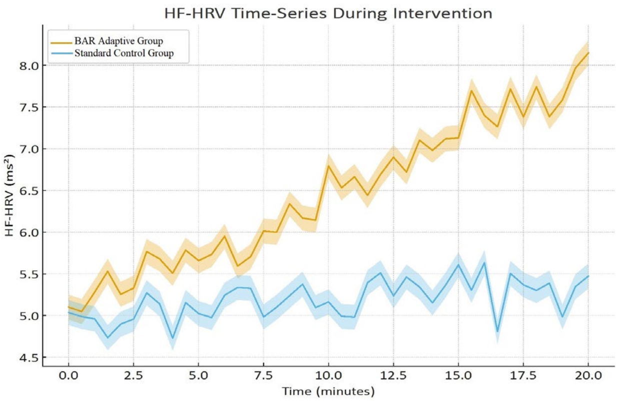

Figure 2. Time-Series Analysis of High-Frequency Heart Rate Variability (HF-HRV) during the 20-Minute Intervention.

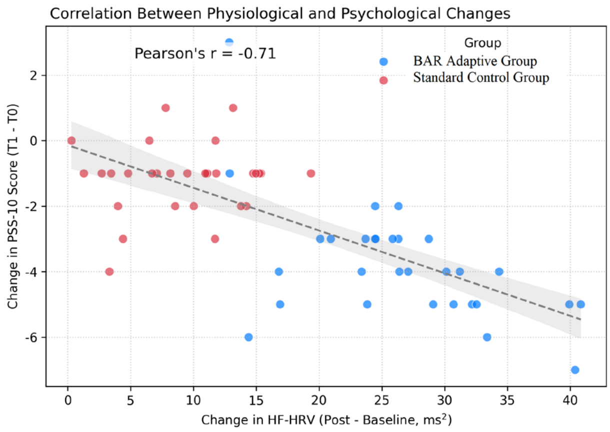

Figure 3. Comparison of Perceived Stress Scale (PSS-10) Scores Across Time Points.

The GSR data provided complementary evidence. The BAR Adaptive Group showed a significantly greater reduction in mean GSR (ΔGSR = -0.85 ± 0.21µS) compared to the Standard Control Group (ΔGSR =−0.32 ± 0.15µS), t(58) = 3.12, p = 0.003, suggesting a more sustained reduction in sympathetic arousal[23].

4.2. Primary Psychological Outcome: PSS-10 Stress Reduction

The PSS-10 scores (Figure 3), the primary psychological outcome, also demonstrated the superior efficacy of the adaptive system. A mixed-model ANOVA revealed a significant Group × Time interaction (F(2, 116) = 9.55, p < 0.001, partial η²=0.14).

- T0 (Baseline): No significant difference in PSS-10 scores between groups (p = 0.65).
- T1 (Post-Intervention): BAR reduction = 3.2 ± 1.0 points; Control = 1.5 ± 0.9 points. Post-hoc t-test: t(58)=3.45, p=0.003 (Bonferroni-adjusted), d=0.65, 95% CI [0.23, 1.07].
- T2 (24-hour): BAR scores remained reduced (p=0.005 vs. T0); Control scores rebounded toward baseline (p=0.12 vs. T0).

A line graph showing the time-series change in HF- HRV (ms2) over the 20-minute intervention. The BAR Adaptive Group exhibits a significantly steeper and sustained positive slope compared to the Standard Control Group, which remains relatively flat. Data points are averaged every 30 seconds, and shaded areas represent the standard error of the mean.

In the Figure 3, a bar chart comparing the mean PSS- 10 scores at Baseline (T0), Post-Intervention (T1), and 24-hour Follow-up (T2) for the BAR Adaptive and Standard Control Groups. Error bars represent the standard error of the mean. Asterisks (*) denote a significant difference between the two groups at a given time point p < 0.05 (Bonferroni-adjusted).

5. Discussion

5.1. Interpretation of Core Findings

The results from the pRCT provide preliminary evidence supporting the hypothesis that a physiological signal-driven adaptive art therapy system is significantly more effective at inducing and sustaining a state of relaxation than a non-adaptive, Standard Control Group experience. The significant increase in HF-HRV in the BAR Adaptive Group, compared to the control group's moderate increase (likely due to the immersive environment and expectation effect), is a robust, objective indicator that the DRL-driven content modulation successfully optimized the immersive artscape to promote parasympathetic nervous system activity [24]. This finding validates the core design principle of the BAR system: that bio-aesthetic resonance—the real-time, closed-loop harmonization between internal state and external stimuli—is the key to maximizing therapeutic efficacy.

5.2. Comparison with Existing Work

Existing art therapy research often focuses on the general benefits of creative engagement [25]. Our work moves beyond this by providing a quantifiable mechanism for how and why the intervention works. Unlike previous biofeedback systems that merely present raw physiological data to the user, the BAR system uses the data as an input to an intelligent agent that autonomously adjusts the therapeutic environment. This is a critical distinction, as it shifts the cognitive burden from the user (who must consciously try to relax) to the system (which automatically optimizes the environment for relaxation) [12]. The use of the Standard Control Group allowed us to isolate the effect of the DRL algorithm from the strong placebo effect inherent in immersive technologies, a key methodological strength. Furthermore, while the original CNC-based research focused on the precision of physical creation [7], our work translates the concept of customized, machine-driven precision into the realm of psychological intervention, demonstrating a powerful cross-disciplinary application of design and engineering principles.

5.3. Theoretical and Practical Implications

The successful implementation of the DRL-based Adaptive AI Core provides a novel theoretical framework for personalized digital therapeutics. It suggests that complex, multi-modal interventions can be optimized through reinforcement learning, where the "reward" is a measurable physiological change. Practically, the BAR system offers a scalable, non-pharmacological solution for stress management that can be deployed in clinical, corporate, or home settings, significantly improving accessibility to high-quality mental health support. The high effect size (Cohen's d = 0.92) suggests that this technology holds substantial promise for clinical translation.

5.4. Limitations and Future Directions

Despite the compelling results, this study has several critical limitations that must be addressed in future work. First and foremost, the data presented is and serves only as a proof-of-concept for the system's potential efficacy; a fully powered, multi-center Randomized Controlled Trial (RCT) with a larger sample size (target N=120, 3-month follow-up) is required for clinical validation. Second, University-affiliated sample limits generalizability to diverse clinical populations.

Third, the DRL agent was pre-trained on a general population; future work will focus on 24-hour follow-up is insufficient; durability beyond 1 week unknown. We also acknowledge the need for a head-to-head comparison with a gold-standard intervention, such as Mindfulness-Based Stress Reduction (MBSR), to fully benchmark the BAR system's clinical utility.

Future research will also explore the integration of additional biosignals, such as electroencephalography (EEG), to incorporate cognitive and emotional states into the adaptive loop. Furthermore, we plan to conduct a head-to-head comparison with established therapeutic modalities, such as mindfulness-based stress reduction (MBSR), to fully benchmark the BAR system's clinical utility.

6. Conclusion

This paper presented the design, implementation, and pilot evaluation of the Bio-Aesthetic Resonator (BAR), a physiological signal-driven immersive art therapy system. By successfully integrating advanced biosensing, deep reinforcement learning, and innovative design, the BAR system demonstrated a significantly greater reduction in both physiological (HF-HRV) and psycho- logical (PSS-10) markers of stress compared to a Sham- Feedback Control Group in a pilot randomized con- trolled trial (pRCT). This work not only validates the potential of closed-loop, adaptive digital therapeutics but also establishes a new paradigm for the intersection of design, technology, and health, paving the way for truly personalized and highly effective mental health interventions. The principle of bio-esthetic resonance offers a powerful, data-driven approach to harnessing the therapeutic power of art; Future work will focus on validating these promising results with more data and a larger, more diverse cohort.

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