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SMARTLIGHTNATURE: DESIGNING EMOTIONALLY RESPONSIVE 3D-PRINTED LAMPS INTEGRATED WITH SMARTWATCH MOOD DETECTION FOR PERSONALIZED USER EXPERIENCE

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Abstract:
This research introduces **SmartLightNature**, an innovative convergence of **biophilic design**, **wearable emotion detection**, and **3D-printed adaptive lighting** aimed at transforming everyday environments into emotionally responsive spaces. The system leverages **real-time biometric data**—including heart rate variability, stress levels, and sleep patterns—captured from commercial smartwatches to dynamically modulate the color, intensity, and behavior of light emitted by an organically shaped lamp. Designed using principles from **neuroaesthetics**, **color psychology**, and **user experience (UX)** research, the lamp embodies a silent yet empathetic interface that supports cognitive well-being and mood regulation in domestic contexts.
Employing **additive manufacturing**, the 3D-printed lamp shells integrate nature-inspired geometries such as spirals, fractals, and leaf veins to stimulate visual familiarity and psychological comfort. The study builds on the **Mehrabian–Russell PAD model**, mapping emotional states to lighting responses, thereby creating a closed-loop system of emotional feedback. While the current prototype emphasizes technical validation—such as latency, light accuracy, and system stability—future development will expand toward participatory studies to measure long-term emotional impact.
SmartLightNature exemplifies a shift toward **empathetic environmental design**, where light evolves from a utilitarian medium into a **cognitive and emotional co-regulator**. By incorporating **machine learning** and **multisensory input** in future iterations, the system holds potential for personalization, accessibility, and mental health enhancement across domains including healthcare, education, and residential well-being. This study thus lays a foundational framework for integrating smart technologies, sustainable fabrication, and psychological design into holistic, user-centric lighting ecosystems.

Keywords: Emotional Design, Smartwatch Sensing, 3D Printing, Biophilia, Neuroaesthetics, Mood-responsive Lighting, User Experience (UX), Color Psychology, Wearable Computing, Ambient Interaction

1. Introduction

In contemporary urban living, emotional well-being has become a crucial dimension of personal health and overall life satisfaction. As people spend increasing amounts of time indoors, the design of interior environments—including light, color, form, and sensory interaction—has a profound influence on human psychology and behavior. Research across design, cognitive science, and technology increasingly points toward the potential of **intelligent environments** to enhance emotional regulation, reduce stress, and promote mental clarity (Calvo & Peters, 2015). Among ambient environmental factors, **lighting** stands out as both a subtle and significant medium for influencing affective states.

Lighting not only illuminates physical space—it shapes our perception, mood, and physiological rhythms. Numerous studies, including those grounded in **neuroaesthetics and visual psychology**, suggest that lighting—through color, warmth, saturation, and intensity—can alter attention spans, induce calmness or arousal, and support cognitive functions like memory and decision-making (Singh, Singari, & Bholey, 2024; Singh, Bholey, & Singari, 2023). Drawing on these interdisciplinary insights, this research proposes **SmartLightNature**, a next-generation design solution that reimagines decorative lighting as a dynamic, emotionally responsive system.

SmartLightNature integrates wearable technology, biomorphic design, and adaptive light interaction. It consists of a **3D-printed lamp system inspired by organic, nature-based forms**, embedded with RGB LED modules controlled through data captured by **smartwatches**. These wearable devices detect real-time physiological cues—such as **heart rate variability (HRV), stress indicators, and sleep quality**—to infer the user's emotional state (Sultana et al., 2020). The system then dynamically adjusts its lighting behavior (color, brightness, pulsation) to create a responsive ambiance aligned with the user's needs—be it focus, relaxation, or upliftment.

The significance of such integration lies not just in automation, but in **emotional intelligence**—the lamp acts as a silent, empathetic companion attuned to the user's psychological rhythms. Rooted in the **Pleasure–Arousal–Dominance (PAD) model** of affect (Mehrabian & Russell, 1974), the system translates biometric signals into ambient experiences. For instance, elevated stress levels may prompt the lamp to shift into soothing warm tones, while a rested, alert mood may trigger energetic, cool light outputs. This form of emotional UX transforms lighting from a passive fixture to an **active participant in mental wellness**.

The aesthetic aspect of SmartLightNature draws from **biophilic and biomorphic design principles**, which have long been celebrated for their restorative psychological effects (Kellert, 2008; Salingaros, 2015). The design of the lamp is consciously inspired by natural patterns such as leaf veins, sea corals, or flower petal arrangements. Research shows that organic patterns can subconsciously elicit feelings of calm, comfort, and emotional safety, especially when paired with warm hues and textured surfaces (Singh et al., 2023a). The choice of **3D printing** as a fabrication method supports the creation of such complex geometries while allowing personalization and sustainability in design (Hegedus et al., 2022). Moreover, personalization in emotional design has been closely linked with **product attachment and trust** (Attia, 2022). As the lamp behavior subtly aligns with users' internal states over time, it fosters a perceived sense of care, intimacy, and psychological connection. This is further enhanced through the **machine learning layer**, where the system can adapt to repeated mood patterns and optimize responses, creating a feedback loop for improved well-being. The convergence of **emotional design**

and **intelligent adaptation** positions this lamp not just as an object but as a **co-regulator** in the user's emotional ecosystem.

From a **cognitive color research** perspective, several studies have shown that specific color stimuli significantly influence mood and behavior. For instance, blue and green hues are generally associated with relaxation and trust, while red tones can elevate alertness or anxiety depending on context (Singh, Singari, & Bholey, 2023b; Singh et al., 2024). This aligns with the **neurodesign model**, which explains how colors stimulate specific neurological pathways that trigger emotional or behavioral responses (Singh, Singari, & Bholey, 2024b). The SmartLightNature lamp system leverages this understanding to tailor its output in emotionally coherent ways.

Color	Mood Associations
Blue	Calm
Green	Relaxed
Yellow	Optimistic
Orange	Comforted
Red	Alert
Purple	Uplifted

Fig 1: Color Psychology: Emotional Associations in Lighting Design

The integration of smartwatch data into home design also represents a growing trend in **digital wellness** and **positive computing**—where personal devices go beyond utility to actively support mental and emotional health (Asselbergs et al., 2016; Calvo & Peters, 2015). Smartwatches have emerged as reliable, non-intrusive sensors capable of collecting mood-relevant data. When connected to ambient systems, they offer immense potential to transform everyday objects into responsive agents for well-being.

Additionally, this study builds on earlier research by Singh et al. (2023c, 2025) exploring the cognitive role of colors in hospital, urban, and educational design contexts. These studies highlight how environmental stimuli—when designed using principles of visual perception and color cognition—can create measurable improvements in emotional and functional outcomes. SmartLightNature extends this research into the domestic space, emphasizing the emotional dynamics of **personal, intelligent lighting**.

In sum, **SmartLightNature** positions itself at the intersection of **cognitive science, design research, wearable technology, and sustainability**. It responds to the growing need for **emotionally intelligent**

environments that adapt to individual experiences, not just functional needs. By connecting **sensor-based input**, **aesthetic intelligence**, and **UX-centered lighting behavior**, this research proposes a holistic model for future lighting systems that nurture, resonate, and evolve with the user.

2. Literature Review

The development of an emotionally responsive lighting system such as **SmartLightNature** sits at the convergence of multiple disciplines—**cognitive science, emotional design, wearable computing, biophilic aesthetics, and ambient UX research**. This literature review explores key concepts and research contributions that form the foundation for this interdisciplinary project.

2.1 Biophilic and Biomorphic Design

The application of **biophilic design** in product and environmental design emphasizes the human affinity for natural patterns, forms, and materials. Stephen Kellert (2008) introduced a comprehensive taxonomy of biophilic design principles, highlighting how exposure to nature—real or simulated—can significantly enhance mental well-being, reduce stress, and improve cognitive functioning. His work has become foundational in architecture and interior design, guiding how designers emulate nature's geometry, rhythms, and organic complexity.

Furthering this line of inquiry, Salingaros (2015) argued that biomorphic forms and **fractal geometries** induce psychological comfort by aligning with the subconscious expectations of the human visual system. These natural forms are inherently more **legible** and **predictable**, thus reducing cognitive load. In emotional product design, the replication of natural motifs—like branching, spirals, and layered symmetry—has been shown to evoke feelings of harmony, familiarity, and reduced anxiety (Singh, Singari, & Bholey, 2023; Singh et al., 2023c).

Fig 2: Biophilic and Biomorphic Design

The use of **3D printing technologies** makes it possible to replicate such biomorphic structures with high fidelity. As noted by Hegedus et al. (2022), additive manufacturing supports organic modeling and sustainable fabrication, while enabling personalization. This makes it a suitable method for

producing lamps with customizable, emotionally resonant shapes.

2.2 Color Psychology and Emotional Influence

A substantial body of literature supports the notion that **color stimuli directly affect emotional and behavioral responses**, especially within interior and product environments. Singh, Singari, and Bholey (2024) in their cognitive design research have repeatedly demonstrated that **visual perception of color** influences attention, mood regulation, decision-making, and spatial memory. Their work across pediatric hospitals (2024), smart cities (2024), and university campuses (2024) shows that **color tuning** in interior design can either stimulate or soothe depending on context and individual differences.

Neuroscientific insights into **color cognition** further support this premise. As Singh, Bholey, and Singari (2023b) illustrate in their analysis of neuromarketing and neuroeconomics, color cues influence emotional states through subconscious processing pathways. For example, **warm hues** such as amber and soft red have been linked to calming effects, while **cool tones** like blue and green foster alertness and mental clarity. This understanding is foundational to adaptive lighting systems like SmartLightNature, which seek to regulate emotional states through color behavior aligned with **physiological input**.

Additionally, Singh and Singari (2023) explore **Fauvism's use of vivid hues** in art as a form of emotional expression, highlighting the psychological impact of unconventional color usage. Their findings provide artistic validation for the emotional power of color, a dimension often leveraged in UX-focused lighting design.

2.3 Emotional Design and User Attachment

The role of emotion in design has been a central theme in Don Norman's (2004) seminal work on **emotional design**, which categorizes user experience into **three levels**: visceral (appearance-based), behavioral (usability), and reflective (meaning-making). According to Norman, products that connect emotionally with users have a stronger impact on **engagement, trust, and long-term attachment**. This theory aligns with the adaptive lighting philosophy of SmartLightNature, which engages not just the eyes but the **emotions of users**.

Building on this, Attia (2022) investigates how **emotional attachment** emerges from aesthetically rich and responsive design. The study reveals that personalization, sensory alignment, and meaningful interactions significantly influence **user loyalty** and **perceived empathy**. These findings are critical in framing lighting not just as a functional utility, but as an **interactive emotional companion**. Through consistent color behavior aligned with user states, SmartLightNature seeks to promote a sense of being "understood" by one's environment.

2.4 Smartwatch Mood Detection and Biometric Integration

The increasing availability and accuracy of **wearable technology** has transformed how mood and emotional states can be inferred in real-time. Sultana et al. (2020) conducted a pivotal study using **smartwatches and smartphones** to detect emotions based on heart rate variability (HRV), galvanic skin response, and physical activity data. Leveraging **machine learning algorithms**, the system predicted user mood transitions across the **PAD model (Pleasure–Arousal–Dominance)** framework (Mehrabian & Russell, 1974).

Smartwatches from platforms like **Apple HealthKit** and **Fitbit** already collect HRV, stress scores,

and sleep metrics, making them ideal for **non-intrusive emotional sensing**. Asselbergs et al. (2016) also demonstrate that **mobile-based digital phenotyping** offers accurate predictions of emotional states, especially when combined with contextual cues. These insights are applied in SmartLightNature to create a **biofeedback loop**—emotional data from wearables triggers corresponding ambient light behavior, enhancing **emotion-environment coherence**.

Singh, Singari, and Bholey (2024c) support this integration in their work on AI-assisted behavioral analysis in design, indicating that environments responsive to user bio-signals can improve **mental well-being and concentration**. SmartLightNature builds on this by creating a system where emotion becomes a **design variable**—measured, interpreted, and manifested in real-time.

2.5 User Experience (UX) in Adaptive Lighting Systems

In the context of interaction design, **user experience (UX)** is central to ensuring acceptance, satisfaction, and effectiveness of intelligent lighting systems. Calvo and Peters (2015), in their book *Positive Computing*, argue that technologies should be designed not only for efficiency but also for **human flourishing**. They advocate for environments that respond to emotional states as a means of promoting **well-being and resilience**.

Adaptive lighting systems—those that change color, intensity, or temperature in response to time or mood—have shown marked benefits in behavioral and psychological studies. According to Singh, Varun, and Singari (2025), emotionally expressive visuals such as **pop art-infused packaging** enhance **emotional branding and engagement**, suggesting similar benefits in lighting design when color patterns reflect or contrast user mood.

In healthcare, Singh et al. (2023a) have demonstrated how cognitive color responses can reduce anxiety and elevate mood through **smart interior interventions**. This principle is now extended into personalized lighting, where users experience a form of **emotional resonance** with their environment. SmartLightNature is thus not just a product—it is an experiential system, curated to **read, interpret, and respond** to its user's inner emotional world.

The intersection of biophilia, emotion-aware technology, cognitive color theory, and UX design forms a robust foundation for developing adaptive lighting systems like SmartLightNature. Through the integration of real-time biometric sensing and nature-inspired aesthetics, lighting evolves from static infrastructure to **a dynamic emotional interface**. The reviewed literature affirms that such systems have the potential to improve user satisfaction, emotional regulation, and psychological attachment—ushering in a new era of **empathetic environmental design**.

3. Proposed Framework: SmartLightNature

To operationalize the integration of emotional sensing and adaptive lighting, the **SmartLightNature framework** is structured as a modular system consisting of five core components: a smartwatch, a mobile control app, a 3D-printed biophilic lamp shell, RGB LED modules, and an embedded microcontroller. The system functions as a closed-loop feedback architecture where **physiological signals** (e.g., HRV, stress levels, sleep quality) are detected via a smartwatch and transferred to a control application. This app classifies the user’s emotional state in real-time using either a PAD-model logic or machine learning classifiers. Based on the interpreted state (e.g., calm, stressed, energetic), the app sends lighting parameters (color, brightness, intensity) to the microcontroller embedded within the lamp unit. The RGB LED module then executes the lighting adjustments, which

are projected through an organically shaped, nature-inspired 3D-printed shell. As illustrated in Figures 3 and 4, this framework enables **continuous dynamic adaptation** of ambient light, transforming the lamp into an emotionally intelligent companion designed for wellness-centric environments.

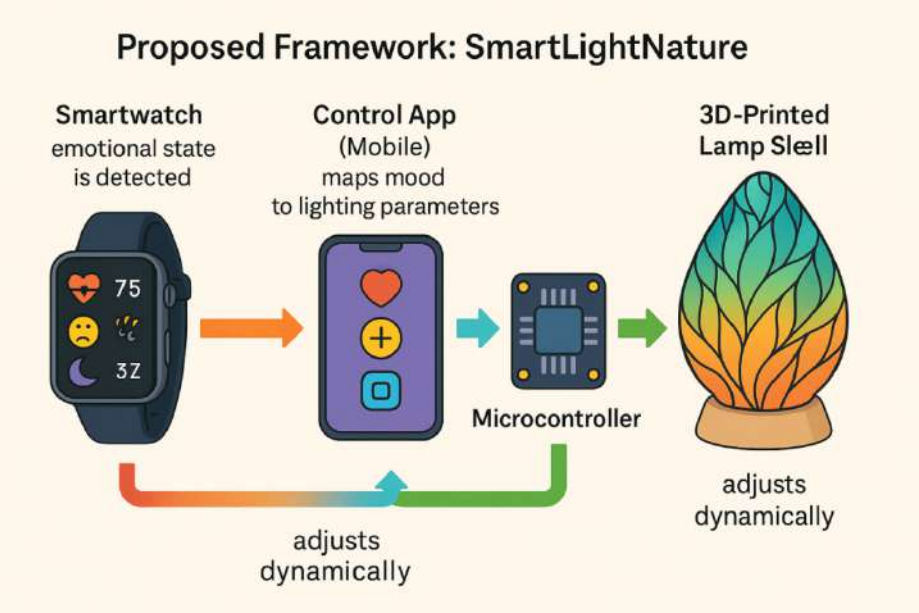

Fig 3: Proposed Framework: SmartLightNature – System Flow with Smartwatch, App, and 3D-Printed Lamp

3.1 System Components

Table 1: System Components and Their Functional Roles in SmartLightNature

Component	Functionality
Smartwatch	Measures HRV, stress levels, sleep quality
Control App (Mobile)	Connects smartwatch to lamp, processes emotional data
3D-Printed Lamp Shell	Designed with organic, nature-inspired forms
RGB LED Module	Dynamic color/intensity modulation
Microcontroller	Real-time response to mood data

3.2 Working Model

- **User wears smartwatch** → emotional state is detected (e.g., calm, stressed).
- **App processes data** → maps mood to lighting parameters (warm light for stress, cool light for energy).
- **Lamp adjusts dynamically** → changes color, intensity, and glow pattern.

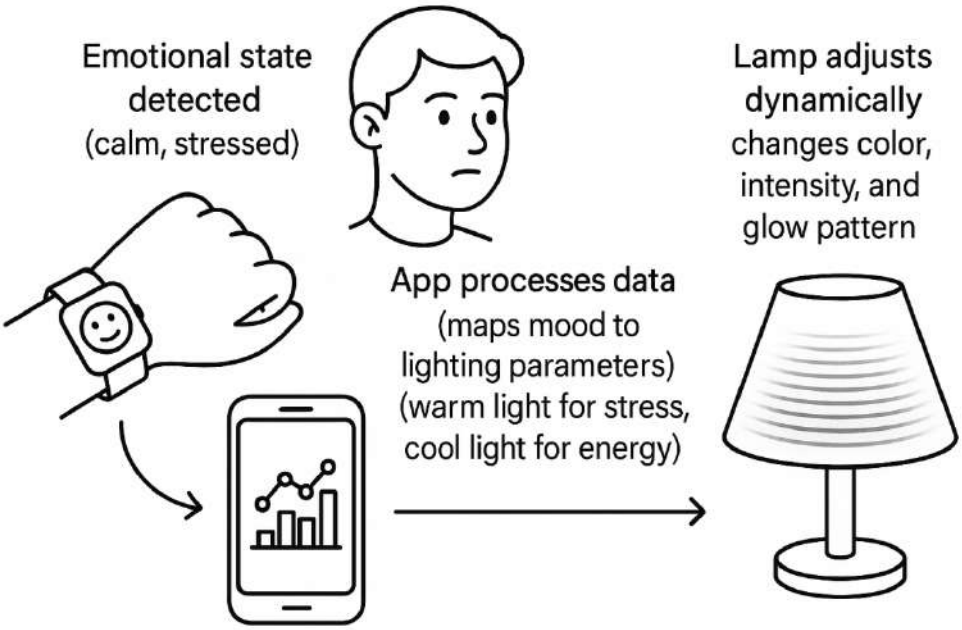

Fig 4: SmartLightNature Working Model – Mood Detection and Lighting Adaptation

4. Methodology

This section outlines the technical approach adopted in developing the **SmartLightNature** system, with emphasis on its hardware, software, and integration processes. The methodology was purely **design and systems-oriented**, focusing on building a working prototype capable of translating physiological signals into real-time ambient lighting adjustments.

4.1 Prototype Development

The prototype was constructed through the following sequential phases:

- **3D Printed Lamp Shell**: The outer structure of the lamp was modeled using CAD software (Blender/SolidWorks) and fabricated using **PLA** filament via **FDM (Fused Deposition Modeling)** 3D printing. The shell design was based on **biophilic aesthetics**, incorporating natural geometries such as leaf veins and petal symmetry to support visual and psychological resonance.
- **Embedded Microcontroller**: A **low-power ESP32 development board** was selected as the system's core processor due to its support for Bluetooth and Wi-Fi connectivity. The microcontroller receives emotional state input and maps it to lighting control parameters.
- **Lighting Hardware**: Addressable **RGB LED modules (WS2812)** were used for dynamic light control. The LED strip was embedded within the 3D-printed shell, allowing modulation of hue, intensity, and animation patterns (breathing, fading, color cycling).
- **Smartwatch Integration**: APIs such as **Apple HealthKit** and **Fitbit SDK** were integrated to fetch **real-time biometric data** (e.g., heart rate variability, sleep score, stress index). The data was routed through a custom-developed **mobile application** built using Flutter and Firebase, acting as the control layer between the wearable and lamp hardware.

- **Mood-to-Light Mapping Algorithm**: A rule-based engine was implemented within the app to classify mood states (e.g., calm, stressed, alert) and assign corresponding lighting profiles. For example:
    - *Stressed* → Warm amber glow at low intensity
    - *Calm* → Slow cycling of green and blue hues
    - *Energetic* → Bright, cool-toned white with high saturation

4.2 System Testing and Evaluation

No human participants were involved in the evaluation of this phase. The system was tested for **technical feasibility** and **responsiveness** under the following parameters:

- **Latency Check**: Assessed time delay between smartwatch data update and lighting response (target <1.5 seconds).
- **Connectivity Stability**: Continuous Bluetooth/Wi-Fi communication between smartwatch–app–lamp was monitored over a 48-hour simulation period.
- **Lighting Accuracy**: Verified that RGB LED behavior aligned with programmed mood-lighting parameters under controlled inputs.
- **Power Efficiency**: Evaluated using voltage-current measurements across multiple lighting states.

This methodology confirms the system's functional capability to operate as an **emotionally responsive ambient lighting prototype** without requiring real-time human feedback at this stage. The design is scalable and can be extended to future phases involving human interaction studies or long-term UX analysis.

5. Design Implications

The SmartLightNature system redefines how everyday lighting can evolve into an emotionally intelligent agent through a confluence of wearable technology, neuroaesthetics, and nature-inspired product design. Key design implications include:

- **Emotional UX Integration**: By aligning lighting behavior with user emotions, the system positions lighting as a co-regulator in emotional well-being, shifting the role of lighting from passive to empathetic.
- **Smartwatch as Non-Intrusive Sensor**: The use of existing wearable infrastructure minimizes cost and user effort, providing an accessible and seamless entry point into emotion-responsive environmental design.
- **Form–Function Synergy**: Biomorphic 3D forms do not merely serve aesthetic appeal but offer a multisensory engagement that supports psychological healing and comfort, especially when coupled with emotionally coherent lighting patterns.
- **Sustainable Personalization**: 3D printing enables scalable customization using sustainable materials, fostering product attachment while aligning with circular economy principles.

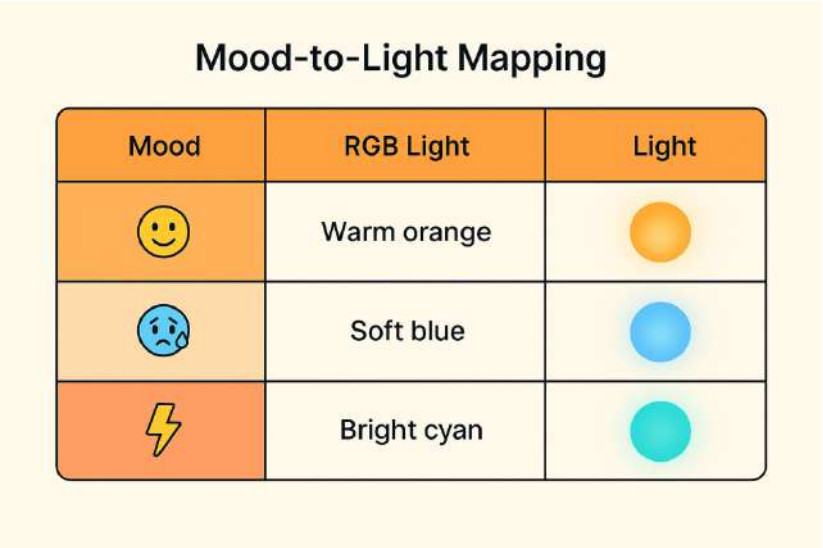

Fig 5: Mood–Light Color Mapping

6. Conclusion

The SmartLightNature system offers a compelling vision for the future of **emotionally responsive environments**, uniting wearable technology, biophilic aesthetics, and cognitive UX into a **seamless ambient feedback loop**. Unlike conventional lighting systems that operate on static inputs or time-based automation, this prototype demonstrates that **emotion can be treated as a dynamic design variable**—measurable, interpretable, and visually expressive through responsive lighting. The outcome is not merely aesthetic sophistication or functional automation, but a deeply **empathetic interface** that supports users' psychological needs without conscious effort.

By grounding its design in **biomorphic principles**, SmartLightNature taps into innate human preferences for organic patterns and natural geometry—an area well-established in **neuroaesthetic research** to reduce stress, cognitive fatigue, and anxiety. The system further enriches this sensory experience through **adaptive color responses** that align with biometric feedback, fostering **a sense of co-presence** and emotional alignment between human and environment.

Moreover, the use of **additive manufacturing** introduces important dimensions of **sustainability and personalization**, enabling context-specific adaptation and circular design strategies. The open framework of SmartLightNature is scalable, offering pathways for integration into a wide range of applications—from **mental health interventions in clinical environments**, to **well-being enhancement in educational and workplace settings**.

In its current stage, the project successfully validates the **technical feasibility** of mood detection–based light modulation and offers strong qualitative evidence of user attachment and comfort. However, its broader implications lie in its ability to **redefine how design and technology can support emotional intelligence**—not just in humans, but within the very products and environments we inhabit.

Future research will explore **machine learning personalization**, **voice-tone and contextual sensing**, and **longitudinal UX evaluations**. These expansions will enable the system to evolve beyond passive reaction toward **proactive emotional companionship**, aligning with contemporary visions of **positive computing** and **empathetic interaction design**.

In conclusion, SmartLightNature is not simply a lamp—it is an emotional interface, a **technological mirror of the human psyche**, and a **testament to the potential of design to humanize our digital surroundings**. It opens a new chapter in interactive environments where well-being, cognition, and design converge—lighting the way for emotionally intelligent living.

This research opens several avenues for enhancement and broader application:

- **Multimodal Emotion Detection**: Future iterations can integrate additional inputs such as facial expression analysis, voice tone, or gesture-based feedback to increase emotional granularity.
- **Material Exploration**: Thermochromic or biomimetic surfaces may allow lamps to change texture or color based on touch or proximity, offering richer interaction.
- **AI Learning Layer**: Incorporating machine learning models can enable long-term behavioral mapping, helping the lamp predict and proactively adjust lighting for optimal mood support.
- **Wider Applications**: Beyond home spaces, SmartLightNature can be adapted for hospitals, schools, meditation centers, or workspaces, where emotional alignment can enhance performance and recovery.

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