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Design of an Arduino-Based Digital Nature Therapy System Integrating Plant Electrophysiology and White Noise Modulation

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Abstract: Under the trend of continuous integration of digital healing and nature interaction, traditional plants are endowed with new technical semantics and emotional values. Based on the "Listening Plant" project, this paper designs and implements a multimodal sound healing system that integrates plant bioelectricity signals acquisition, white noise sound template generation, and emotional keyword input. The project constructs a three-dimensional mapping logic of "emotion-plant-sound" through Human-Centered Interaction Design, perceptual computing, and Acoustic Psychology. This study presents a novel interaction design paradigm centered on natural co-sensing for the digital healing field, offering value for both application and emotional intervention.

Keywords: Plant Bioelectrical Signals; Multimodal Interaction; Sound Healing; Affective Design; Human-Centered Interaction; Natural Synesthesia

1. Introduction

In the modern life of intense work pressure and information explosion, an increasing number of people are experiencing mental subhealth phenomena: anxiety, insomnia, loneliness, attention deficit, and emotional regulation disorders have become common problems. According to the World Health Organization (WHO) report in 2022, more than 970 million people around the world suffer from different degrees of psychological stress, with the elderly and young people living alone being the hardest hit (World Health Organization, 2022). At the same time, people are actively looking for alternative means of healing, and Digital Healing has gradually become an emerging direction of emotional intervention due to its scalability, customization, and intelligence (Fürstenau et al., 2023).

Modern neuropsychological studies have demonstrated that natural sounds are highly beneficial for reducing the effects of white noise. In particular, continuous and uniform sounds such as rain, wind, and water flow can effectively cover environmental noise and help people to focus or fall asleep (Torous et al., 2020). At the same time, plants, as a kind of non-verbal life form, have always carried the symbolic meaning of "empathy", "companionship," and "growth" in East Asian culture. Moreover, plants construct "symbolic boundaries" through chemical/electrical signals to form symbolic expressions of environmental stress(Buxton et al., 2021). Current technology can capture and visualize the bioelectrical signals of plants through sensory conversion devices, which provides a technological basis for building a "human-nature-technology" emotional bridge.

This project aims to build a multimodal sound healing system that integrates plant electrical signal acquisition, emotional keyword input, and white noise template modulation, and to provide a personalized and participatory healing experience through the collaboration of dual platforms of software and hardware.

2. Methodology

2.1 Design Research Methodology

This study integrates the use of Human-Centered Interaction Design, Perceptual Computing, and Psychoacoustics to achieve accurate perception of the user's emotional state and personalized intervention. The specific methodological paths are as follows:

Human-Centered Interaction Design: Focusing on the daily interaction scenes between users and plants, we adopt Participatory Design to collect users' keyword input preferences in emotional states such as meditation, loneliness, anxiety, and then build a multi-dimensional interaction model (Houde & Hill, 1997).

Perceptual Computing: Based on the Arduino acquisition module, the system performs real-time monitoring and data cleansing of plant bioelectric signals, using timing analysis and frequency mapping algorithms to convert the electric signals into adjustable sound parameters (e.g., pitch, rhythm, loudness)(Picard, 2010).

Acoustic Psychology: Combining the existing white noise intervention research results (Buxton et al., 2021), we verified the efficacy of different natural sound templates in regulating the emotional state and optimized the audio configurations through the feedback of user tests (Zwicker & Fastl, 2013).

The research process emphasizes the integration of "data-driven and emotional design", which takes into account the responsiveness of the system and the empathy of the user, and provides methodological support for the construction of a multimodal intelligent healing system.

The design adopts the triple approach of Human-Centered Interaction Design, perceptual computing, and acoustic psychology:

Table 1: Application of the theory and method of "Human-Centered Interaction Design + perceptual computing + acoustic psychology"

Methodology Category	Application
Human-Centered Interaction Design (HCI)	Through the APP page, the user selects keywords and records emotions, obtains keyword categorization and audio preference, focuses on the interaction path in daily meditation, and loneliness.
Perceptual Computing	Using plant electrodes with an analog-to-digital conversion module to capture electrical signals, mapping pitch, rhythm, and other audio factors based on fluctuating frequencies;
Acoustic Psychology	Analyzing the intervention differences of different white noise types on users' psychological states (concentration, relaxation, and falling asleep), and constructing a library of white noise templates;

2.2 Selection of design carriers

We choose the Spathiphyllum as the core interactive plant of "Listening Plant", based on the dual logic of bioelectric characteristics measurability and the suitability of human-plant interaction experience, and construct the basis for decision-making through the indirect derivation of the literature across the research object and the analysis of the two-dimensional sensory characteristics:

(1) Measurability of bioelectric signals and indirect evidence support. Although there is no direct literature to confirm that "touching the Spathiphyllum will change its electrical signals", it can be indirectly deduced through the study of electrical signals of similar plants and the commonality of plant stress mechanisms:

Similar plants research basis: through the jasper, Spathiphyllum's electrical signal analysis shows that the dual-tree complex wavelet noise elimination combined with NAR neural network model, the coefficient of determination of Spathiphyllum shows a high degree of goodness of fit, proving that its electrical signal has a regular stability and can be monitored for the external stimulus (such as touch) triggered by the change in the signal to provide the "signal can be captured" premise(Hagihara et al., 2022).

Commonality of plant stress mechanisms: Mimosa pudica produces electrical signaling changes mediated by calcium ions when it is stimulated (phytophagous insect attack). Combined with the commonality of plant physiology and the cross-species similarity of plant stress response, it can be reasonably inferred that Spathiphyllum may also generate electrical signal fluctuations when stimulated by touch, which provides a biosignal basis for human-plant interaction(Gao et al., 2017).

(2) Sensory adaptation design for human-plant interaction

In addition to the basis of bioelectric signals, the characteristics of Spathiphyllum in the visual and tactile dimensions are highly compatible with the interaction design needs:

Visual guidance: the leaf vein texture is clear, naturally forming the "interaction electrode contact localization reference". Users can intuitively recognize the electrode's action area, which reduces the operation learning cost and strengthens the perceptibility of the "human-plant-signal" association.

Tactile feedback: The thickness of the leaf blade and the elasticity of touch pressure are moderate. It not only avoids the operation risk of "fragility" of thin leaves, but also gets rid of the tactile defects of "stiffness and obstruction" of thick leathery leaves, and gives the user natural, comfortable, and repeatable interaction feedback, which is in line with the demand of ergonomics on the interaction experience.

2.3 Design Process

System structure construction: builds the initial interaction framework by dividing the hardware and software modules. The hardware collects the electrical signals, and the software is responsible for analyzing and playing them, forming a closed-loop interaction chain.

Design of keyword emotion system: reference to the emotion chromatography theory and daily language collection, establish a three-dimensional keyword system of "emotion-environment-time", such as "anxiety-rainy day-night" corresponding to a specific template.

Sound template design: establishes a basic white noise library, including rain, water, birdsong, wind, with adjustable parameter interfaces (e.g., rhythm, frequency, loudness, etc.) for each template.

Plant data mapping mechanism establishment: through the actual measurement of plant current data, mapping its fluctuation frequency, amplitude change, etc., to pitch, rhythm, and dynamic change factor, realizing the dynamic modulation of music variable structure.

App front-end interaction construction: develop the mobile interface, including keyword selection, device connection, audio playback, and rhythm feedback module.

Prototype Testing and Optimization: Conducts scenario testing in different emotional scenarios, such as young white-collar singletons living alone after work and young white-collar singletons living alone before going to sleep, records the feedback and satisfaction of the experience, and conducts system fine-tuning and parameter optimization.

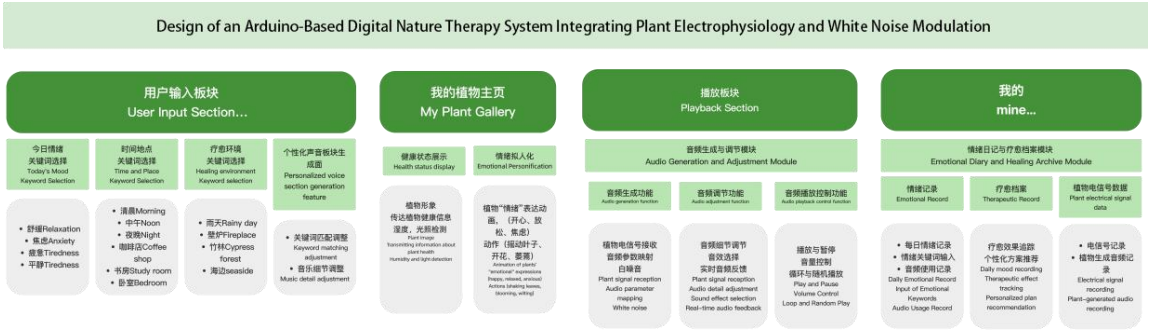

Figure 1. Application Information Design Diagram

3. Application Design

As the emotional regulation center of human-plant interaction, the App side of the system undertakes the core functions of emotional input, device connection, sound generation, and user feedback etc. The interface and interaction logic of the system are designed around "healing, sensibility, and intuitiveness", aiming to provide users with a simple and emotionally connected digital empathy platform.

3.1 Module Architecture and Function Classification

Emotional Keyword Input Module: Users select the current emotional state, time of day, and environmental factors (e.g., "anxiety + night + rainy day") by clicking or sliding, and the system generates the initial values of the corresponding sound templates accordingly to achieve personalized initial settings.

Device Connection and Status Feedback Module: It supports one-key pairing with Arduino plant hardware via Bluetooth, displays plant status (power, light, humidity) and connection feedback, and provides real-time synchronization tips.

Audio Generation and Adjustment Module: The system receives plant bioelectrical signals in real time, maps them into audio parameters (such as rhythm, frequency, pitch) through algorithms, and generates multi-dimensional white noise (rain, wind, water, etc.). Users can fine-tune the sound parameters according to their preferences to personalize the listening experience (Lee, 2024).

Emotional diary and healing archive module: the user's daily usage records and keywords will generate an emotional usage map, which can track the trajectory of emotional fluctuations and realize future AI audio recommendations, providing a data basis for long-term psychological state regulation.

3.2 Page Design

The App interface is designed with the core logic of emotional neutrality, visual load reduction, and natural mimicry to build a positive impact from the perceptual layer to the emotional layer:

Emotional regulation of low-saturated colors: a low-saturated green and beige color scheme is used; green is associated with natural healing imagery, beige reduces visual oppression, and the two synergistically reduce the user's sense of anxiety.

According to color psychology, low-saturation hues can activate the brain's "relaxation response", weakening stress and creating a quiet, soothing atmosphere.

Cognitive adaptation of natural mimicry: The natural environment is simulated through plant graphics and gradient effects, which are in line with humans' innate affinity for nature. This mimetic design can trigger the brain's positive cognitive association with natural scenes, enhance psychological comfort, and strengthen the "natural connection" experience of human-plant interaction.

4. Scenario Application and Healing Logic

The application logic of the system is based on the three-phase healing path of "emotion recognition - sound response - user adjustment", emphasizing that the active participation of the user and the perception feedback of the natural system form a closed loop of emotional resonance.

4.1. User Scenario

User profile: 28 years old, a working young man, facing high pressure of the project, anxiety, and fatigue at the same time.

Typical use path: After work, when the user inputs the emotion keyword "tired + rainy day" through the mobile terminal, the system first encodes it as an explanatory symbol and builds a symbolic interpretation framework. This framework triggers Bluetooth commands to activate the plant electrodes, which collect the bioelectric signals from the leaves of the Spathiphyllum in real time. When the user touches the leaf and triggers the caring behavior, a harp overtone + bamboo flute upward melody, as well as wind and birdsong, are generated in real time. When the user stops touching, a running water sound base is generated in real time, superimposed on a cello fluctuating long tone(Lee, 2024).

Among them, the running water sound is the most effective in enhancing positive and healthy emotions, while the birdsong sound is the most effective in relieving stress and worries (Buxton et al., 2021).

4.2 Healing Logic

The healing logic of this system is based on the three-phase path of "external natural stimulation - emotional perception mapping - sound intervention feedback", emphasizing the empathic interaction mechanism between the user and the natural media.

Firstly, the system introduces "natural feedback" through the dynamic collection of plant bioelectrical signals, which serves as a non-verbal emotional mirror and enhances the user's perceptual empathy experience(Trewavas, 2003); secondly, the user completes the labeling of his/her own emotions through the input of keywords, which guides the system to enter the phase of context matching and sound template retrieval; lastly, based on the real-time fluctuation of plant signals, the system dynamically modulates the parameters of the sound template in terms of rhythm, frequency and other dimensions, thus realizing the auditory "emotional response" (Kosmyna et al., 2019).

This process not only endows the sound with individualized biological characteristics but also prompts the user to establish a subjective emotional connection to the "plant response", which in turn evokes a sense of companionship, control, and healing, and achieves the goals of lowering anxiety, improving sleep, and enhancing the ability to regulate emotions (Baumel, 2022). This logic has been validated in studies, where natural sound interventions have been shown to reduce cortisol levels and have both physiological and psychological healing potential.

5. Discussion

5.1 Innovations

The core innovation of this project is reflected in four dimensions:

First, it is the first time that plant bioelectric signals are mapped to sound parameters in real time, breaking through the previous unidirectional playback mode that relies only on fixed white noise templates;

Secondly, the project proposes a three-dimensional generation framework of "emotional keywords + plant signals + generative audio", and introduces time-series feature extraction and progressive modulation algorithms to make the sound output highly personalized and dynamic;

Thirdly, we construct a closed-loop co-sensory interaction path between hardware and software, where the user's touch behavior is both the trigger point of plant data collection and the starting point of emotional self-labeling, which strengthens the active participation and feedback perceptibility.

Fourth, it emphasizes the mutual feedback mechanism between caregiving behavior and emotional healing, and promotes the sense of companionship and responsibility through anthropomorphic plant characters, which verifies the feasibility and transferability of the digital co-care model in psychological intervention.

5.2 Reflection

In terms of reflection, three limitations of the project remain:

(1) The plant bioelectrical signals are significantly affected by environmental temperature and humidity and electrode contact stability, resulting in high data noise, and the subsequent need to introduce multi-channel redundant acquisition and adaptive filtering (Sun et al., 2023).

(2) The current sound templates are constructed based on expert experience, with limited variety and style. Long-term use may lead to auditory fatigue, so it is necessary to combine deep

generative networks to expand materials and continuous learning based on the user's historical preferences (Ferguson et al., 2023).

(3) Lacking large-sample and long-cycle clinical validation, the healing effect of the system mainly relies on subjective scales and small-scale experiments, and in the future, we should cooperate with medical organizations to introduce physiological indicators such as Heart Rate Variability and Electrodermal Activity to establish an objective evaluation system.

Attention should be paid to data privacy and psychological ethics to ensure the safety of emotional data and the interpretability of the intervention process, and to avoid the problems of digital dependence and technological alienation. The hardware should be further lightweight to enhance the flexibility of deployment at home and in public spaces.

6. Conclusions

By integrating plant bioelectric signals and multimodal interaction technology, this project constructs a sound healing system centered on natural empathy and creates a new path of three-dimensional "emotion-plant-sound" interaction. The project is designed to transform from passive audio playback to dynamic co-sensory generation, which not only enhances the personalization and immersion of digital healing but also strengthens the users' active participation and psychological connection in the process of emotional regulation (Gaekwad et al., 2022).

As the interaction hub of the system, the App side builds a complete process covering emotional input, plant connection, audio generation, and feedback tracking, so that the technology is no longer cold but becomes an emotional carrier with a personalized response. Although there are still technical challenges, such as data acquisition stability and audio material richness, the overall design logic and system architecture have shown good expandability and application prospects.

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