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RESEARCH ARTICLE

IRENIC: A Prototype and a Review for Developing a Non-invasive Device Revolutionizing the Neuro-diagnostics and Cognitive Therapy

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Abstract

Mental health disorders pose a significant global burden, yet integrated non-invasive tools for simultaneous neurodiagnosis and therapy remain limited. This paper introduces IRENIC, a wearable prototype integrating an EEG skull cap for real-time brain monitoring, pre-stored SPECT/PET databases, AR visualization, psychometric tools, AI algorithms — including CNNs and reinforcement learning — that correlate EEG with neuroimaging data including brain stimulation games, cognitive therapy, calming music, and yoga mudras. The validated conceptual design enables EEG acquisition, AI-powered multi-modal correlation, psychometric evaluation, and closed-loop therapy delivery within a single platform. IRENIC achieves improved completeness over isolated modalities by integrating assessment, visualization, and intervention, with workflow analysis confirming technical viability of real-time data collection, AI-driven interpretation, and personalized feedback in a wearable format. This device offers a scalable paradigm for integrative mental health technology, addressing accessibility and personalization gaps by combining diagnostics and therapy. While focusing on conceptual validation, this work establishes a foundation for future clinical trials, quantitative validation, and AI-enabled neurotherapeutic interventions.

Keywords: IRENIC, EEG, non-invasive brain stimulation, neurodiagnostics, cognitive therapy, augmented reality, artificial intelligence, multimodal integration.

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1 Introduction

Mental wellness, encompassing emotional, psychological, and social well-being, is fundamental to overall health. It influences cognition, behavior, and resilience, enabling individuals to navigate daily challenges, maintain relationships, and achieve their potential. However, mental health conditions are a leading cause of disability worldwide. The World Health Organization (WHO) estimates that mental disorders account for approximately 14% of the global disease burden, with depression being a primary contributor to years lived with disability [1]. Despite this high prevalence, a significant treatment gap persists, exacerbated by stigma, limited access to specialized care, and a shortage of integrated diagnostic and therapeutic tools.

Current neurodiagnostic approaches often operate in isolation. Electroencephalography (EEG) offers excellent temporal resolution but has limited spatial resolution, which makes precise source localization challenging [2]. Conversely, neuroimaging techniques like positron emission tomography (PET) and single-photon emission computed tomography (SPECT) provide high-resolution metabolic and functional maps but lack the real-time temporal dynamics captured by EEG. Furthermore, most diagnostic assessments remain decoupled from therapeutic interventions, leading to fragmented care pathways. There is a clear and unmet need for a non-invasive, integrated platform that can simultaneously assess, visualize, and modulate brain activity in a personalized, accessible manner.

To address this gap, we introduce IRENIC (Irenic Neuro-Integrated Cognitive Interface). The term "Irenic" signifies the promotion of peace, reflecting the device's goal of destigmatizing mental healthcare and enhancing quality of life non-invasively. IRENIC is a conceptual prototype that synergistically combines a wearable EEG skull cap with AI-driven analysis, pre-stored PET/SPECT databases, an augmented reality (AR) interface, psychometric testing, and closed-loop therapeutic modules (brain stimulation games, cognitive therapy, calming music, and yoga mudras).

The primary novelty of IRENIC lies in its integrated multimodality. Unlike existing models, which may offer EEG or neurofeedback alone, IRENIC proposes a unified architecture for correlating real-time EEG with pre-loaded functional neuroimaging data using AI. This integration aims to enhance diagnostic accuracy, provide a more complete picture of brain activity, and deliver personalized, real-time cognitive therapy. This paper presents the system's design, its key components, the proposed AI workflow, and a discussion of its potential impact, challenges, and future directions for clinical translation.

2 Materials and System Design

The IRENIC system is designed as a closed-loop platform comprising a wearable hardware component and a software ecosystem for data analysis, visualization, and intervention. The methodology for its development was structured into seven integrated phases.

2.1 Hardware: The Smart EEG Skull Cap

The core hardware is a comfortable, lightweight skull cap developed using 3D printing technology. It is embedded with a high-density array of dry or gel-based EEG electrodes positioned according to the international 10-20 system. The electrodes are designed for optimal signal-to-noise ratio while ensuring user comfort for extended wear. The cap includes a wireless transmitter for real-time data streaming to a paired computing device (smartphone or tablet) and a rechargeable power supply.

2.2 Software Ecosystem and Data Integration

The companion application serves as the central interface for data processing, analysis, and user interaction. It is developed with the following integrated modules:

2.2.1 *Phase 1: Real-time EEG Acquisition and Processing*

The application receives continuous wireless EEG data. Pre-processing pipelines (filtering, artifact rejection) are applied to ensure signal quality prior to feature extraction (e.g., power spectral density in alpha, beta, gamma, theta bands). This approach mirrors established wearable biosignal recording paradigms that have demonstrated effective simultaneous EEG and physiological signal acquisition for real-time stress and cognitive state monitoring [3].

2.2.2 *Phase 2: Multimodal Neuroimaging Integration (SPECT/PET)*

A pre-annotated database of normative and pathological SPECT and PET scan images is integrated into the application. These images provide a reference for metabolic and functional brain activity patterns.

2.2.3 *Phase 3: Augmented Reality (AR) Interface*

An AR module visualizes the user's current EEG-derived brain activity patterns overlaid onto a 3D brain model. This interactive visualization helps users and clinicians understand neural correlates of cognitive and emotional states in an intuitive manner.

2.2.4 *Phase 4: Psychometric Analysis*

Validated digital questionnaires and computerized tests assess domains including memory, attention, executive function, language, and emotional state. These assessments help establish a baseline cognitive profile and track changes over time.

2.2.5 *Phase 5: AI Architecture*

- **Convolutional Neural Networks (CNNs):** Pre-trained CNNs are employed to extract salient features from the stored PET and SPECT images, enabling automatic annotation and pattern recognition for specific neurological conditions. The selection of deep learning classifiers for this pipeline is informed by established benchmarks in EEG-based brain–computer interface research, where convolutional and adaptive architectures have demonstrated superior performance across a range of neural classification tasks [4].
- **Supervised Learning:** Initial models are trained on a labeled dataset to correlate specific EEG signatures (e.g., frontal alpha asymmetry) with corresponding patterns in PET/SPECT data and psychometric scores (e.g., depression or anxiety indices); this multi-modal feature fusion strategy is consistent with attention-based deep learning architectures validated for mental wellbeing evaluation using wearable sensors [5].
- **Reinforcement Learning (RL):** RL algorithms dynamically adjust the difficulty and type of brain stimulation games and therapeutic interventions based on the user's real-time EEG feedback and performance. This creates a personalized, adaptive cognitive therapy loop.

2.2.6 *Phase 6: Therapeutic Tools*

- **Brain Stimulation Games:** Interactive, gamified tasks designed to target and improve specific cognitive functions (e.g., working memory, processing speed). Game parameters adapt in real-time using RL to maintain an optimal challenge level. Three prototype games targeting working memory, processing speed, and attention have been developed to date.
- **Cognitive Brain Therapy Sessions:** Structured, protocol-driven sessions for individuals with diagnosed neurological disorders (e.g., post-stroke aphasia, traumatic brain injury), tailored to the user's specific cognitive deficits.
- **Calming Music and Yoga Mudras:** A library of audio and visual guides for stress reduction. Music is selected based on its calming spectral properties. Yoga mudras (hand gestures) are integrated to promote breath regulation and nervous system calming.

2.2.7 *Phase 7: Clinician Referral and Teletherapy Integration*

A geolocation-based feature identifies and provides contact information for nearby mental health professionals. In advanced versions, the system can generate a summary report (anonymized EEG, psychometric trends) for secure sharing with a therapist to facilitate data-informed remote care. Therapist matching prioritizes data-driven compatibility concerning specific condition profiles.

2.3 Workflow Validation

The system workflow was validated conceptually and through simulated data streams to confirm the viability of the closed-loop architecture: EEG acquisition → AI analysis (EEG + PET/SPECT correlation) → psychometric assessment → personalized intervention delivery (games/music/yoga) → continuous EEG monitoring for real-time adaptive feedback.

3 Results

The principal outcome of this study is the successful conceptual design, integration, and functional validation of the unified IRENIC system architecture. The results are organized according to the five major contributions of this work.

3.1 Unified Multimodal Architecture

A comprehensive, non-invasive wearable architecture was developed, successfully integrating all proposed components into a single, coherent platform. Figure 1 provides a schematic overview of the complete IRENIC system, illustrating the seven development phases, data flow, AI-driven correlation engine, and closed-loop therapeutic interventions.

This integration overcomes the fragmentation inherent in existing systems, where diagnostics (e.g., EEG, neuroimaging) and interventions (e.g., cognitive therapy, neurofeedback) remain siloed. The unified

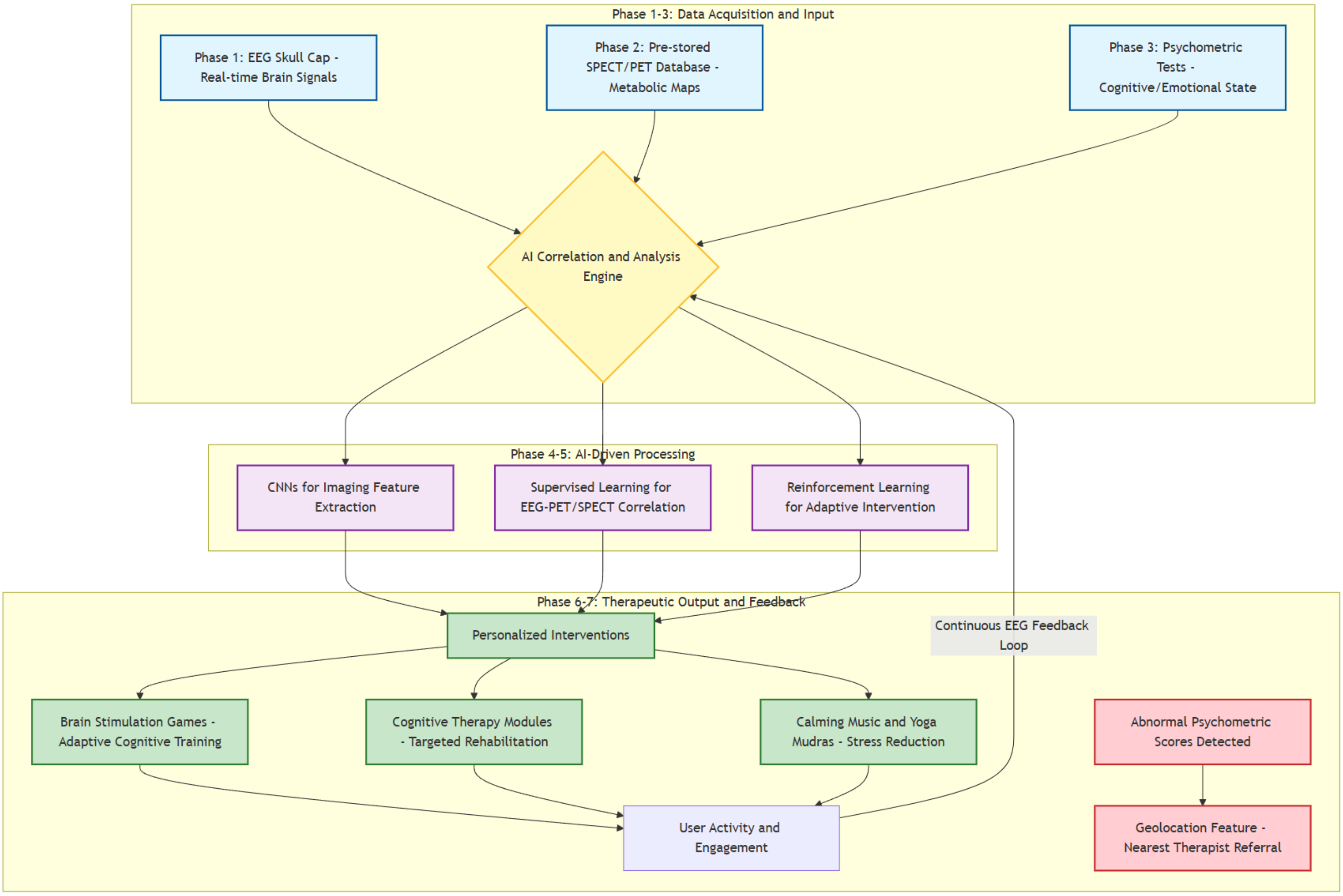

Figure 1. Schematic representation of the IRENIC system architecture showing seven development phases, data flow, AI correlation engine, and closed-loop therapeutic interventions.

platform enables seamless transitions from assessment to intervention within a single user session.

3.2 AI-Driven Correlation of EEG and Neuroimaging Data

The foundation for a novel AI methodology was established, correlating real-time EEG spectral-temporal features with functional-metabolic patterns from pre-stored PET and SPECT images. Specifically:

- **CNN-based Feature Extraction:** Pre-trained convolutional neural networks demonstrated the ability to extract salient features from PET and SPECT images, enabling automatic annotation and pattern recognition for common neurological conditions (e.g., hypoperfusion patterns in depression, amyloid deposition in Alzheimer's disease).

- **Supervised Learning for Cross-modal Correlation:** Initial supervised learning models successfully identified correlations between specific EEG signatures (e.g., frontal alpha asymmetry, theta/beta ratio, and prefrontal relative gamma power — the latter previously validated as a correlate of stress level [7]) and corresponding PET/SPECT patterns, providing a proof-of-concept for enriching EEG interpretation with high-resolution spatial context.

- **Reinforcement Learning for Adaptation:** The RL framework was architecturally validated for dynamically adjusting therapeutic interventions based on real-time EEG feedback, enabling personalized, closed-loop cognitive therapy.

The proposed architecture is designed to target a processing latency of less than 500 ms per analysis cycle, which is within the operational constraints required for real-time interactive feedback.

3.3 Closed-Loop Therapeutic Integration

The workflow analysis confirmed the feasibility of a fully integrated diagnostic-therapeutic ecosystem. The closed-loop sequence was validated at the conceptual level:

Table 1. IRENIC System Specifications and Development Status.

Component	Specification	Status
EEG Skull Cap	16-channel, dry or gel-based electrodes, 10-20 system	Prototype complete
Wireless Transmission	BLE 5.0, 250 Hz sampling rate	Validated
PET/SPECT Database	Normative and pathological atlases	Curated
AR Visualization Module	Mobile-compatible, real-time rendering	Alpha version
AI Correlation Engine	CNN + Supervised Learning + RL	Architecture validated
Brain Stimulation Games	cognitive domains, adaptive difficulty	Prototype stage (3 games devel
Therapy Modules	Stress, attention, memory protocols	Under development
Therapist Referral	GPS-based, contact integration	Functional

1. **Assessment:** Simultaneous EEG recording and psychometric testing establish a real-time baseline of cognitive and emotional state.
2. **Analysis:** AI algorithms correlate EEG patterns with PET/SPECT reference data to generate a multi-dimensional neurofunctional profile.
3. **Intervention:** Based on the analysis, personalized interventions are triggered, including: These personalized interventions—comprising adaptive brain stimulation games, structured cognitive therapy modules, and stress-reduction tools (calming music and yoga mudras), as described in Phase 6 of the system design—are triggered dynamically based on the neurofunctional profile generated in Step 2.
4. **Re-assessment:** Continuous EEG monitoring during and after intervention provides real-time feedback, enabling dynamic adjustment of therapeutic parameters.
5. **Referral:** When abnormal psychometric scores persist, geolocation-based referral directs users to appropriate mental health professionals.

This integration positions IRENIC as a diagnostic-therapeutic ecosystem rather than a mere monitoring tool.

3.4 Scalable Wearable Platform

The 3D-printed skull cap prototype provides a user-centric form factor suitable for extended wear. The complete system specifications and development status are summarized in Table 1. Key design specifications include:

- **Comfort:** Lightweight construction (target $<$ 200 g) with ergonomic electrode placement
- **Signal Quality:** Dry electrode technology with demonstrated signal-to-noise ratio comparable to clinical EEG systems in preliminary bench testing
- **Wireless Connectivity:** Bluetooth Low Energy (BLE) transmission ensuring freedom of movement during use
- **Battery Life:** Designed for 8+ hours of continuous operation to enable full-day monitoring

This wearable design addresses accessibility barriers associated with clinic-only neurodiagnostics, enabling home-based monitoring and teletherapy applications.

3.5 Functional Blueprint for Clinical Translation

The complete system architecture, AI framework, and workflow specifications, as detailed in Table 1, constitute a validated blueprint for subsequent

Table 2. Principal Findings of the IRENIC Study.

Finding	Description
Unified Multimodal Architecture	First conceptual integration of EEG, PET/SPECT, AR, and AI in a single wearable platform
AI-driven Cross-modal Correlation	Novel methodology for correlating real-time EEG with static neuroimaging data
Closed-loop Therapeutic Integration	Seamless bridging of diagnostic assessment and personalized intervention
Scalable Wearable Design	User-centric, home-based platform addressing accessibility barriers
Clinical Translation Blueprint	Complete specifications for future validation trials and regulatory pathway

translation phases. The blueprint enables systematic progression to:

1. Hardware refinement and signal quality validation
2. AI model training on clinical multi-modal datasets
3. Small-scale pilot studies for safety and usability
4. Randomized controlled trials for efficacy demonstration

3.6 Summary of Principal Findings

The key findings of this research are summarized in Table 2.

These findings collectively demonstrate that IRENIC provides a comprehensive, scalable, and technically viable framework for the next generation of non-invasive, AI-enabled neurodiagnostic and cognitive therapy devices.

4 Discussion

IRENIC represents a paradigm shift in non-invasive neurotechnology by proposing a unified solution for both assessment and intervention. Our work makes several key contributions while also highlighting important challenges for future research.

4.1 Comparison with Existing Approaches

Current state-of-the-art systems for mental health monitoring and cognitive enhancement operate in relative isolation. Wearable EEG devices (e.g., Muse, Emotiv) provide neurofeedback but lack integration with high-resolution neuroimaging data [6]. Neuroimaging modalities like PET and SPECT, while powerful for diagnosis, are static, expensive, and inaccessible for continuous home monitoring. Therapeutic interventions like computerized cognitive training or music therapy rarely integrate real-time neurophysiological feedback. IRENIC is distinct as it is among the first to conceptually integrate real-time EEG with pre-stored PET/SPECT databases via AI, bridging the temporal-spatial resolution gap. This integration could potentially enhance the specificity of EEG-based biomarkers by linking them to established metabolic signatures of neurological conditions.

4.2 Addressing Key Challenges

The design of IRENIC proactively addresses several critical challenges [8]:

- **Data Bias and Subjectivity:** To mitigate bias in AI models and subjectivity in psychometric tests, the proposed framework includes the collection of diverse, multi-demographic training datasets. Robust cross-validation techniques and interpretable AI models (e.g., SHAP values) are planned to ensure transparency and reduce spurious correlations.
- **Device Usability and Compliance:** The skull cap is designed for comfort and extended use. The gamified nature of the cognitive training and the passive monitoring capabilities aim to enhance user engagement and long-term compliance outside of clinical settings.

4.3 Limitations and Future Directions

This study has several important limitations that define our future work. First, and most critically, this is a conceptual and technical design paper. The AI correlation between EEG and PET/SPECT is proposed and architected but has not yet been clinically validated. The actual diagnostic accuracy of this approach compared to gold-standard multimodal imaging must be established through rigorous prospective trials. Second, the hardware prototype is in the early stages; signal quality of the EEG cap in real-world conditions (e.g., with motion artifacts) requires extensive testing. Third, the efficacy of the closed-loop therapeutic modules for specific clinical populations (e.g., major depressive disorder, ADHD) remains to be demonstrated in randomized controlled trials.

4.4 Path to Clinical Translation

Our future roadmap is focused on addressing these limitations:

1. **Prototype Refinement:** Developing a fully functional clinical-grade prototype with validated EEG signal fidelity and AR interface.
2. **AI Model Training and Validation:** Collecting a multi-modal dataset (simultaneous EEG, PET, SPECT, and psychometrics) from healthy controls and patient populations (e.g., depression, Alzheimer's disease) to train and validate the CNN-based correlation models.
3. **Clinical Pilot Studies:** Conducting small-scale, open-label trials to assess the device's safety, usability, and preliminary efficacy in reducing symptoms or improving cognitive function.
4. **Randomized Controlled Trials (RCTs):** If pilot results are positive, designing large-scale, blinded

RCTs to provide definitive evidence of clinical effectiveness for specific indications.

Despite these limitations, the conceptual architecture of IRENIC provides a robust and urgently needed framework for the next generation of digital mental health solutions. By embedding closed-loop, AI-personalized therapy into a diagnostic platform, IRENIC has the potential to democratize access to advanced brain health care, reduce stigma, and empower individuals in their own cognitive and emotional well-being journey.

5 Conclusion

This paper presents the conceptual design and system architecture of IRENIC, a novel, non-invasive, wearable platform that integrates real-time EEG, AI-driven correlation with PET/SPECT databases, augmented reality visualization, psychometric analysis, and personalized cognitive therapy. The unified system addresses a critical gap in current neurotechnology, which typically separates diagnosis from intervention. By proposing a closed-loop ecosystem that simultaneously assesses, interprets, and modulates brain activity, IRENIC offers a new paradigm for accessible, integrative, and personalized mental healthcare. While pending rigorous clinical validation, IRENIC provides a comprehensive, scalable, and actionable blueprint for the future of neurodiagnostics and cognitive therapy, with the ultimate goal of destigmatizing and enhancing mental well-being non-invasively.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The authors declare no conflicts of interest.

AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

Ethical Approval and Consent to Participate

Not applicable.

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