Integrated BCI Platform for Cognitive Performance Enhancement through Multisource Biosignal Analysis and Adaptive Stimulation

Computer Science Department

Academic Year: 2025/2026

Final Year Project Proposal

Contents

1 Abstract

Imagine a platform that not only reads your mind in real-time but understands why you lose focus, offering targeted, science-backed solutions. This graduation project introduces a comprehensive AI-driven platform that revolutionizes cognitive performance optimization. The system integrates affordable EEG monitoring (NPG Lite), physiological data (smartwatch), and advanced Retrieval-Augmented Generation (RAG) AI to accurately detect cognitive states, identify the underlying causes of focus decline (e.g., sleep, nutrition), and provide multi-modal interventions. The platform is delivered through two specialized entities: a Mobile Application (HazeClue) for personalized cognitive management (monitoring, training, and optional adaptive stimulation), and a separate Web Platform (ParallelScore) for objective, multi-user educational assessment. The architecture relies on server-side processing for complex analysis and client-side control for safety and device management, offering a unified, reliable, and evidence-based BCI solution.

2 Project Overview

The human brain operates as a silent black box, constantly processing and sending subtle signals about focus and fatigue. This project develops an intelligent BCI Platform that opens a precise window into that black box. Our system goes beyond simple measurement; it diagnoses the root causes of cognitive decline by cross-referencing neural patterns with physiological data (HRV, sleep quality).

The platform is designed to serve two distinct, high-impact user groups through specialized products:

- **HazeClue: The Personalized Cognitive Co-Pilot (Mobile App)**
  HazeClue is the individual-focused tool that provides holistic cognitive management. It offers continuous, real-time focus monitoring, utilizes built-in Cognitive Training Tools (exercises, binaural beats), and provides evidence-based advice generated by the RAG AI engine to address the cause of the focus loss. For users who opt-in, it manages the optional adaptive tDCS stimulation with rigorous, client-side safety controls. Crucially, HazeClue users can monitor their focus and utilize all training features without ever enabling tDCS, catering to a wide range of personal needs.

- **ParallelScore: The Objective Educational Analyst (Web Platform)**
  ParallelScore addresses the need for objective assessment in education. It is a separate, group-focused web dashboard enabling educators to monitor the real-time neural engagement and collective attention of multiple students simultaneously during content consumption (via multi-device Wi-Fi streaming). This provides a

scientifically valid metric for evaluating content effectiveness and teaching styles.

3 Problem Statement

In today's demanding society, sustained cognitive performance is essential, yet individuals and institutions face challenges related to:

- Attention deficits and mind-wandering during critical tasks without effective, data-driven support tools.
- Cognitive fatigue limiting peak performance, coupled with a lack of personalized tools to identify and address the root causes of focus decline (e.g., nutritional deficiencies impacting cognition).
- Absence of objective methods to evaluate educational content quality or teaching styles' impact on student engagement.
- Risks associated with neurostimulation without intelligent, safety-governed, client-side control.

4 Competitive Advantages & Core Features

Feature/Advantage	**HazeClue (Individual Focus)**	**ParallelScore (Group Analysis)**
Causal Analysis & Advice	Advanced RAG AI: Identifies reasons for focus loss (e.g., Magnesium deficiency, low sleep), and provides intelligent, evidence-based recommendations.	Automated Content Evaluation: Generates automated reports and timelines, highlighting content segments that caused the greatest drop in neural engagement.
Control Logic	Client-Side Safety & Closed-Loop: The Flutter app hosts the complete tDCS control logic, ensuring safety limits (20-min counter) are managed locally.	Multi-Stream Data Handling: Robust .NET Backend handles simultaneous, high-frequency data streams from multiple ESP32 devices over standard Wi-Fi.
Holistic Training	Integrated Training Tools: Offers on-demand Cognitive Exercises and Binaural Beats. User engagement provides crucial feedback to the AI system.	Objective Metrics: Replaces subjective feedback with quantitative, neurologically derived metrics.

5 Proposed Solution: Integrated System Modules

5.1 Neural and Cognitive Performance Analysis

- **Focus Score Calculation:** Determined by the Python Engine on the server, based on the power ratio of Beta (β) waves (focus) relative to Alpha (α) and Theta (θ) waves (distraction).
- **Multi-Dimensional Baseline:** Integrates with smartwatch data (sleep quality, HRV) for holistic analysis.

5.2 Health Monitoring, Nutritional Insights, and Causal Analysis (RAG AI)

This module is the core of HazeClue's intelligence, identifying the root cause of focus decline:

- **Predictive Analytics:** Correlates long-term EEG patterns with physiological data to identify potential nutritional deficiencies.
- **Intelligent Alerts and Advice:** The RAG Pipeline queries a specialized scientific Knowledge Base to generate evidence-based alerts recommending lifestyle changes or blood tests.

5.3 Intelligent Adaptive Stimulation (tDCS) - Optional and Client-Controlled

This module is optional and client-side controlled to ensure safety:

- **Client-Side Closed-Loop Control:** The Flutter App receives the Focus Score and runs the complete control logic (Score check, Safety counter, Consent check) to activate the tDCS device (certified commercial device) via Bluetooth.
- **Safety Enforcement:** Enforces the 20-minute cumulative daily limit locally.

5.4 Cognitive Training and Support

This module offers non-electrical, active support integrated into HazeClue:

- **Binaural Beats:** Users can listen to frequency-specific auditory stimulation.
- **Cognitive Exercises:** Built-in exercises (e.g., memory, attention tasks).
- **Feedback Loop:** User performance in these activities is recorded as feedback to refine the AI's future personalized recommendations.

5.5 Educational Content Evaluation System (ParallelScore Web Platform)

- **Multi-User Data Collection:** Collects and aggregates EEG data simultaneously from multiple NPG Lite devices over Wi-Fi.
- **Attention Mapping:** Generates timelines and heatmaps for the instructor.

6 Technical Approach

6.1 System Architecture and Data Flow

Project	Path of Raw EEG Data	Control Logic Location	Processing Location
HazeClue	NPG Lite → Flutter App → .NET Backend → Python Engine	Client-Side (Flutter App)	Server-Side (Python)
ParallelScore	NPG Lite → Wi-Fi Router → .NET Backend → Python Engine	Server-Side (Centralized)	Server-Side (Python)

6.2 Development Technologies

Technology stack: Python, C# with .NET Core, Flutter, React.js/Vue.js

7 Research Questions

The project aims to provide evidence-based answers to the following engineering and scientific research questions:

- **Closed-Loop & Safety:** How can the client-side Flutter application be engineered to reliably enforce all safety interlocks (e.g., automated 20-minute limit, required user consent) while maintaining direct control over the tDCS device via Bluetooth?
- **Focus Score Accuracy:** How can a 3-channel EEG signal be reliably translated into a real-time Focus Score to effectively inform the client-side adaptive intervention logic?
- **AI & Causal Analysis:** How can a Retrieval-Augmented Generation (RAG) architecture be successfully implemented to generate evidence-based causal insights from multisource biosignals for personalized recommendations?
- **Multi-User Scalability:** What is the optimal architecture required to reliably ingest, process, and aggregate simultaneous, high-frequency EEG data streams from multiple ESP32 devices (ParallelScore), ensuring minimal latency for real-time educational feedback?

8 Expected Deliverables and Success Criteria

8.1 Expected Deliverables

- **HazeClue Mobile Application (Flutter):** Fully functional app with BLE connectivity, cognitive training tools, and client-side tDCS control logic.
- **ParallelScore Web Platform (.NET/React):** Functional web dashboard with multi-user Wi-Fi data ingestion and visualization of group focus.
- **Backend API & Engine (.NET/Python):** Robust server system hosting the Focus Score Python engine and the RAG pipeline.

8.2 Success Criteria (Metrics for Validation)

- **Real-time Latency:** Focus Score calculation and round-trip display in HazeClue must be achieved with a latency of less than 1 second.
- **Closed-Loop Reliability:** The client-side application must demonstrate 100% compliance with the 20-minute cumulative safety limit across all test sessions.
- **RAG Accuracy:** The RAG system must successfully retrieve and integrate contextually relevant scientific information into the weekly report analysis with high contextual accuracy ($> 85\%$).
- **Scalability (ParallelScore):** The backend must successfully ingest and display aggregated data from at least 10 simultaneous ESP32 devices without crashing or significant data loss.

9 Implementation Plan

10 Conclusion

The successful completion of this research will establish new foundations for affordable, evidence-based cognitive technology. The projects final architecture, relying on server-side processing for intelligence and client-side control for safety, ensures both innovation and reliability, delivering a comprehensive solution for cognitive optimization and educational assessment.

Period	Phase	Description
First Semester (20 Sept 2025 – 22 Jan 2026)		
20 Sept – 10 Oct	Idea Research	Literature review on EEG, tDCS, LLM, and learning engagement.
10 – 30 Oct	System Design	Create system architecture and UML diagrams.
1 – 20 Nov	Documentation (v1)	Write proposal draft and define system components.
20 Nov – 31 Dec	Core Development	Build EEG focus scoring model and educational platform prototype.
Jan 2026	Mid-Term Demo	Present initial prototype and submit midterm report.
Second Semester (Feb – Jun 2026)		
Feb – Mar	System Integration	Connect mobile app, EEG, smartwatch, and tDCS modules.
Mar – Apr	AI & LLM Development	Implement RAG-based LLM and personalized recommendation engine.
Apr – Mid May	Cloud & Analysis	Deploy cloud data hub and develop integrated dashboard.
Late May – Jun	Final Evaluation	System testing, documentation, and final presentation.