A Modular Simulation Framework for Cognitive Brain Activity with Kalman Filter Integration

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Abstract

This paper presents a modular simulation framework for modeling cognitive brain activity. The system integrates Kalman filters for adaptive learning and monitors perceptual discrepancies to trigger escape behavior. Each brain region is modeled as a functional module, and the simulation incorporates visual, auditory, and linguistic inputs. The language analysis system is based on a novel approach named **Modified Edinburgh Dual-Language Analysis**, which enables parallel semantic and syntactic evaluation by comparing linguistic input with the internal world model constructed by other brain regions.

1 Introduction

Understanding cognitive processes through simulation provides insights into brain function and behavior. This framework models various brain regions and their interactions using structured input signals and neurotransmitter dynamics. The simulation is designed to be extensible for future human brain modeling.

2 Methodology

The simulation includes modules for major brain regions such as the Prefrontal Cortex, Striatum, Hippocampus, Amygdala, Hypothalamus, Cerebellum, Midbrain, Brainstem, Visual Cortex, Language Area, and Auditory Cortex. Each module processes specific types of input and contributes to the overall cognitive state.

2.1 Language Processing: Modified Edinburgh Dual-Language Analysis

The Language Area module employs a dual-pathway approach inspired by the Edinburgh school of linguistic analysis, integrating both syntactic and semantic processing. This has been refined into a **Modified Edinburgh Dual-Language Analysis**, which not only enables nuanced detection of linguistic discrepancies and cognitive dissonance across modalities, but also compares linguistic input with the internal world model generated by other brain regions (e.g., Visual Cortex, Hippocampus, Striatum). This comparison allows the system to evaluate whether the meaning of a sentence aligns with the current perceptual and memory-based context, thereby achieving grounded and context-aware language understanding.

Naming and Conceptual Foundation. The term **Modified Edinburgh Dual-Language Analysis** reflects a fundamental shift from traditional linguistic models. While the original Edinburgh approach emphasized syntactic and semantic duality, the modified version introduced here redefines semantic understanding as a process of *cross-modal alignment with the internal world model*. In this framework, language is not interpreted in isolation, but is continuously compared against perceptual, emotional, and memory-based representations generated by other brain regions. Meaning emerges only when linguistic input is consistent with this internal model. Thus, the "modification" lies in grounding language in the broader cognitive architecture, making it a truly integrative and biologically plausible mechanism.

2.2 Kalman Filter Integration

The Striatum module uses a Kalman filter to update dopamine levels based on reward prediction errors. This adaptive mechanism allows the system to learn from feedback and adjust neurotransmitter levels accordingly.

2.3 Escape Mode Activation

Discrepancies between visual, auditory, and linguistic inputs are monitored. If the discrepancy exceeds a threshold for a sustained duration, the system activates escape mode, suppressing input signals and reducing dopamine levels.

2.4 Consumption History

The simulation includes a consumption history that influences neurotransmitter levels based on past physiological responses to stimuli.

2.5 Visual Cortex Enhancements

The Visual Cortex module currently uses a simplified model based on average image signal intensity modulated by glutamate levels. Planned enhancements include:

- **Binocular Vision:** Integration of stereo image pairs to estimate depth using disparity maps, enabling spatial awareness and object localization.
- **Segmentation:** Boundary-based segmentation using edge detection to isolate distinct visual regions.
- **Semantic Labeling:** Classification of segmented regions into categories such as "food" or "object" based on size and contextual features.
- **Hierarchical Processing:** Future expansion to model visual areas V1, V2, and V4 for layered feature extraction and attention modulation.

3 Simulation Flow

- External Stimuli + Initial Input Signal → Combined Input
- Combined Input → Processed by Brain Regions
- Visual Input → Visual Cortex
- Linguistic Input → Language Area (Modified Edinburgh Dual-Language Analysis)
- Auditory Input → Auditory Cortex
- Outputs from All Regions → Discrepancy Evaluation
- Discrepancy → Escape Mode Activation (if threshold exceeded)
- Reward Signal → Striatum → Kalman Filter → Dopamine Update
- Hippocampus Output → Memory Integration with Input Signal
- Updated Neurotransmitters → Next Simulation Step

4 Results

The simulation produces time-series data of cognitive discrepancies and visualizations of perceptual mismatch. These outputs help analyze the system's response to various stimuli and internal states.

5 Conclusion

This framework provides a foundation for simulating cognitive brain activity. The integration of Modified Edinburgh Dual-Language Analysis and Kalman filter-based learning enables dynamic adaptation and realistic modeling. By grounding language understanding in the internal world model, the system achieves context-sensitive interpretation. Planned enhancements to the Visual Cortex module will enable richer spatial and semantic processing, contributing to more human-like perception and behavior.

Appendix: Toward Autonomous Artificial Intelligence

This framework is designed to evolve toward a fully autonomous artificial intelligence system. The following components outline the future development strategy:

- **Realistic Brain Modules:** Each brain region will be refined using biologically plausible mathematical models, enabling more accurate simulation of neural dynamics and inter-regional communication.
- **World Model via Unity:** A 3D interactive environment will be constructed using Unity to serve as the system's world model. This environment will provide visual, auditory, and physical stimuli, allowing the AI to perceive, act, and learn in a simulated but realistic world.
- **Integration with Large-Scale Models:** The modular brain simulation will be connected to large-scale language and vision models (e.g., LLMs, multimodal transformers) to enhance symbolic reasoning and generalization capabilities.
- **Closed-Loop Interaction:** The system will operate in a closed loop, where perception, cognition, memory, and action are continuously updated based on environmental feedback and internal state changes.
- **Emergent Autonomy:** Through iterative learning and world-model alignment, the system will develop autonomous behavior, capable of goal-directed planning, adaptive response, and context-aware communication.
- **Oxford Engine for Motor Control:** A remaining key component is the development of the **Oxford Engine**, a motor control system that interfaces with a homunculus-like body map. This module will translate high-level motor intentions from the Prefrontal Cortex and Cerebellum into coordinated physical actions within the simulated environment. The Oxford Engine will be responsible for posture, locomotion, and fine motor control, completing the sensorimotor loop essential for embodied intelligence. Its design will incorporate a somatotopic representation (homunculus) to ensure biologically plausible mapping between cortical motor commands and body movements.

This roadmap represents a biologically inspired, mathematically grounded, and computationally scalable path toward general-purpose, self-regulating artificial intelligence.