Supplementary Material S1: Computational Methodology

The Neuro-Computational Architecture of SAIM v9.2:
Bilateral Forehead Fusion & Adaptive Gain Control

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Abstract

This document provides the definitive mathematical specification for the SAIM Analysis Engine v9.2. To robustly quantify the transition from Central Prediction Error Neglect (FSF) to Active Inference (Plasticity), the engine implements a **Bilateral Forehead Fusion** protocol using Modified Beer-Lambert Law (MBLL) and **Adaptive Reliability Gating**.

1 1. Hemodynamic Capacity (HEMO)

The HEMO index proxies the metabolic cost of updating the internal generative model. To maximize signal fidelity, we integrate data from both Left and Right Inner sensors.

1.1 1.1 Bilateral MBLL Inversion

We isolate Oxyhemoglobin concentration changes ($\Delta[HbO_2]$) from the Left ($k = L$) and Right ($k = R$) Inner sensor pairs ($\lambda_{red} = 660\,\text{nm}$, $\lambda_{ir} = 850\,\text{nm}$).

$$\begin{bmatrix} \Delta[HbO_2]_k(t) \\ \Delta[HbR]_k(t) \end{bmatrix} = \frac{1}{d \cdot DPF} \cdot \mathbf{E}^{-1} \cdot \begin{bmatrix} -\ln(I_{Red,k}/\bar{I}_{Red,k}) \\ -\ln(I_{IR,k}/\bar{I}_{IR,k}) \end{bmatrix} \tag{1}$$

The extinction coefficient matrix $\mathbf{E}$ is adopted from Prahl [1]:

$$\mathbf{E} = \begin{bmatrix} 0.087 & 0.730 \\ 0.052 & 0.032 \end{bmatrix} \text{mM}^{-1}\text{cm}^{-1} \tag{2}$$

Parameters: Inter-optode distance $d = 3.0\,\text{cm}$, Differential Pathlength Factor $DPF = 6.0$.

1.2 1.2 Spatial Integration & Activation

The global Hemodynamic Capacity is derived by averaging the volatilities (σ) from valid hemispheres.

$$\sigma_{global} = \frac{1}{N_{valid}} \sum_{k \in \{L,R\}} \sigma(\Delta[HbO_2]_k) \tag{3}$$

This raw volatility is transformed via a thermodynamic activation function:

$$\text{HEMO} = \frac{1}{1 + \exp\left(-\left(\ln(\sigma_{global} \cdot \phi) - \theta\right)\right)} \tag{4}$$

Constants: $\phi = 1000$ (Unit Scaling), $\theta = 2.0$ (Thermodynamic Noise Floor).

2 2. Neural Somatic Order Parameters

To construct the global state space, we define four additional metrics derived from EEG, Accelerometry, and HRV.

2.1 2.1 Free State Index (FSI): Neural Precision

FSI quantifies the cortical Excitation/Inhibition (E/I) ratio.

$$R_{raw} = \ln\left(\frac{P_\gamma + \epsilon}{P_\delta + \epsilon}\right), \quad \text{FSI} = \frac{1}{1 + \exp(-R_{raw})} \tag{5}$$

2.2 2.2 Somatic Order (SOM): Physical Stability

SOM measures the precision of the descending anti-gravity model.

$$\text{SOM} = \frac{1}{1 + \sigma(\|\mathbf{a}\|)} \tag{6}$$

2.3 2.3 Prediction Error Proxy (PE): Uncertainty

Unresolved prediction error is approximated by the volatility of the Alpha rhythm (P_α).

$$\text{PE} = \frac{\sigma(\text{Detrend}(P_\alpha))}{\mu(|P_\alpha|) + \epsilon} \tag{7}$$

2.4 2.4 Autonomic Complexity (AUT): Flexibility

Autonomic flexibility is quantified via the Shannon Entropy H of the heart rate distribution.

$$\text{AUT} = \frac{-\sum p(x) \ln p(x)}{\ln N_{bins} + \epsilon} \tag{8}$$

3 3. Neural Complexity Index (NCI)

3.1 3.1 Adaptive Reliability Gating (ARG)

Weights are dynamically renormalized to exclude sensors below the noise floor ($\epsilon_{noise} = 10^{-6}$).

$$w'_i = \frac{w_i \cdot \mathbb{I}(\text{Var}(i) > \epsilon_{noise})}{\sum_{j \in \mathcal{M}} w_j \cdot \mathbb{I}(\text{Var}(j) > \epsilon_{noise})} \tag{9}$$

3.2 3.2 Composite State Definition

The global order parameter is computed as the sigmoid activation of the integrated score:

$$\text{NCI} = \frac{1}{1 + \exp\left(-\left[\sum_i (w'_i \cdot M_i) - \lambda \cdot \text{PE}\right]\right)} \tag{10}$$

3.3 3.3 NCI Volatility (Criticality Index)

To quantify the phase transition state (Self-Organized Criticality), we calculate the sliding-window volatility of the NCI.

$$\text{NCI}_{Vol}(t) = \sigma(\text{NCI}(t))_{window} \tag{11}$$

A spike in NCI Volatility indicates the destabilization of the fixed attractor (FSF), creating a window for plasticity.

4 References

[1] Prahl, S. A. (1998). Optical absorption of hemoglobin. *Oregon Medical Laser Center.*