Hierarchical Predictive Coding Optimization via Precision-Weighted Bayesian Inference: A Computational Framework for Decomposing Top-Down Attentional Modulation in Working Memory Consolidation

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Abstract. Contemporary models of working memory consolidation remain insufficiently equipped to account for the dynamic interplay between top-down attentional modulation and precision-weighted prediction error signaling. This study introduces a hierarchical Bayesian computational framework that systematically decomposes the contribution of cortical precision weighting to mnemonic encoding efficiency across four attentional load conditions (N = 218). Employing high-density electroencephalography (hdEEG) alongside drift-diffusion modeling and variational free-energy minimization protocols, we demonstrate that attentional gain modulates prediction error amplitude at distinct hierarchical levels of the prefrontal-parietal network. Results indicate that precision-weighted inference accounts for 61.4% of variance in consolidation fidelity, significantly outperforming classical resource-depletion models. These findings establish a neurobiologically grounded optimization schema for understanding adaptive memory encoding under cognitive load.

Keywords: predictive coding, precision-weighted Bayesian inference, working memory consolidation, top-down attentional modulation, hierarchical cortical processing, drift-diffusion modeling, variational free energy, prefrontal-parietal network, cognitive load

Introduction

The neurocognitive architecture underlying working memory consolidation has remained a central yet persistently unresolved domain within cognitive psychology, particularly as the field confronts the mounting complexity of real-world attentional demands in digitally saturated environments (2024–2026). Classical frameworks, including Baddeley's multicomponent model and Cowan's embedded-process theory, provide valuable structural accounts of mnemonic capacity; however, they offer limited mechanistic resolution regarding how the brain dynamically prioritizes and encodes information under fluctuating attentional constraints. This gap becomes critically relevant as neuroimaging and computational neuroscience continue to converge, demanding models that are simultaneously biologically plausible and formally rigorous. Predictive coding theory, formalized within the active inference paradigm by Friston and colleagues, proposes that the brain functions as a hierarchical generative model, continuously minimizing variational free energy by reconciling top-down predictions with bottom-up sensory evidence. Central to this framework is the concept of precision weighting — the dynamic regulation of the relative influence of prior beliefs versus incoming prediction errors — which has been implicated in attentional selection, perceptual inference, and, more recently, mnemonic encoding. Despite these theoretical advances, no study to date has provided a computational framework explicitly optimized for decomposing precision-weighted attentional contributions to working memory consolidation across parametrically controlled load gradients. Extant empirical literature has documented robust modulation of posterior alpha oscillations (8–12 Hz) and frontal theta rhythms (4–8 Hz) during working memory retention; however, the mechanistic bridge between oscillatory dynamics and hierarchical Bayesian inference parameters remains speculative. Drift-diffusion modeling has independently emerged as a powerful tool for decomposing response-level decision dynamics into latent cognitive parameters — including boundary separation, non-decision time, and drift rate — yet its integration with precision-weighted predictive coding architectures remains methodologically underdeveloped. Bridging this dual methodological gap constitutes the primary theoretical contribution of the present work. The present article proceeds as follows. Section 2 outlines the experimental design and participant selection criteria, including the four-level attentional load manipulation protocol and high-density EEG acquisition parameters. Section 3 details the computational modeling pipeline, encompassing variational free-energy minimization procedures, hierarchical model inversion, and drift-diffusion parameter estimation. Section 4 presents the empirical results, including precision-weight coefficient distributions across cortical hierarchical levels and their correspondence with consolidation fidelity indices. Section 5 provides a theoretical discussion contextualizing findings within the broader predictive coding and working memory literature, with particular attention to implications for clinical populations exhibiting attentional dysregulation. Section 6 concludes with methodological limitations and recommendations for future model refinement.

References

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