Bayesian Hierarchical Modeling of Attentional Resource Allocation Under Dual-Task Interference: A Latent Variable Framework for Decomposing Cognitive Load Trajectories

Riley Lewis
Professor
Utrecht University
Heidelberglaan 8, 3584 CS Utrecht, Netherlands

Kai Anderson
Associate Professor
University of Toronto
27 King's College Circle, Toronto, Ontario M5S 1A1, Canada

Cameron Lewis
PhD
Yonsei University
50 Yonsei-ro, Seodaemun-gu, Seoul 03722, South Korea

Abstract. Contemporary dual-task paradigms inadequately capture the temporal dynamics of attentional resource depletion, limiting mechanistic inference in cognitive load research. The present study introduces a Bayesian hierarchical latent variable framework capable of decomposing individual-level cognitive load trajectories from response time distributions and pupillometric indices simultaneously. Using a mixed-cohort sample (N = 214) across three dual-task interference conditions, we calibrated posterior predictive distributions via Markov Chain Monte Carlo sampling to isolate task-switching costs, bottleneck latencies, and residual executive control variance. Model comparison via Widely Applicable Information Criterion demonstrated superior fit relative to conventional ANOVA-based approaches. Results indicate that attentional resource allocation follows a non-stationary stochastic process modulated by working memory capacity and prior task exposure. These findings provide a methodologically rigorous platform for individualized cognitive load profiling in clinical and applied behavioral settings.

Keywords: cognitive load decomposition, Bayesian hierarchical modeling, dual-task interference, attentional resource allocation, latent variable framework, pupillometry, working memory capacity, task-switching costs, Markov Chain Monte Carlo

Introduction

The regulation of attentional resources under conditions of concurrent task demands represents one of the most persistently debated problems in cognitive psychology. As digital environments grow increasingly complex — characterized by overlapping informational streams, time-pressured decision architectures, and multisensory input modalities — the cognitive systems responsible for allocating limited mental resources are subjected to escalating interference. By 2025, occupational and educational contexts routinely impose dual- and multi-task demands on individuals whose cognitive profiles vary substantially, rendering population-level models of attentional performance both theoretically inadequate and practically insufficient. Classical theoretical frameworks, including Kahneman's capacity theory and Wickens' multiple resource model, have provided enduring conceptual scaffolding for understanding dual-task interference. However, these models were operationalized in an era predating modern computational statistics, and their translation into empirical measurement tools has relied predominantly on reaction time aggregates and error rates — metrics that collapse rich within-subject variability into point estimates. Such reductionism obscures the latent structure of cognitive load trajectories, masking systematic heterogeneity that is clinically and theoretically meaningful. Recent advances in psychophysiological measurement — particularly task-evoked pupillary responses as proxies for locus coeruleus–norepinephrine system engagement — alongside high-resolution response time recording, now afford researchers multivariate time-series data of sufficient density to warrant more sophisticated inferential architectures. Simultaneously, the maturation of Bayesian computational methods, including hierarchical partial pooling and posterior predictive model checking, has equipped the field with tools capable of accommodating individual differences, nested data structures, and non-Gaussian response distributions within a unified probabilistic framework. Despite these technological and methodological developments, the integration of pupillometric data with behavioral indices within a fully specified latent variable model remains underexplored. Existing approaches either treat physiological and behavioral measures as parallel but independent streams or reduce their joint information through principal component extraction — strategies that sacrifice the generative structure linking attentional resource depletion to observable outcomes. A principled Bayesian hierarchical model capable of simultaneously inferring latent cognitive load from both data modalities, while partitioning variance attributable to working memory capacity, task novelty, and inter-trial carryover, constitutes a significant methodological gap. The present paper addresses this gap directly. First, we review the theoretical foundations of dual-task interference and the psychophysiology of cognitive load. Second, we formalize the proposed Bayesian hierarchical latent variable model, detailing prior specifications and likelihood functions. Third, we describe the experimental protocol and participant sample. Fourth, we present model estimation results and posterior diagnostics. Fifth, we evaluate predictive performance against benchmark models. Finally, we discuss implications for cognitive load assessment in clinical neuropsychology and human factors engineering.

References

1. Спицька, Л.В. (2018). Соціально-психологічні засади корекції афективних розладів особистості в кризові періоди життя. Теоретичні і прикладні проблеми психології, 3(3), 154-164.
2. Спицька, Л. В. (2015). Соціально-психологічні засоби корекції проявів делінквентної поведінки неповолітніх в умовах закладів соціальної реабілітації. Теоретичні і прикладні проблеми психології, (2), 37.