Longitudinal Modulation of Heart Rate Variability During Progressive Cognitive Load

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Background: Cortical-autonomic interactions enable bidirectional coupling between executive cognition and cardiovascular regulation via prefrontal–subcortical pathways. The autonomic response to cognitive load is poorly understood in longitudinal settings, as well as the role of cardiac-derived features in encoding task-specific processes or the level of cognitive engagement. To date, most studies rely on single-session cross-sectional protocols, limiting characterization of within-subject heart rate variability (HRV) dynamics during repeated cognitive engagement. This study investigates longitudinal HRV modulation across five days during resting and cognitively demanding conditions.

Methods: Thirteen healthy young adults (22 ± 3 years) completed five sessions comprising Resting State 1, Memory task (MEM), Resting State 2, Strategy task (STR), and Resting State 3 for five days. Task difficulty was systematically manipulated across days by progressive removal of cues, enforcing a shift from guided execution to memory retrieval. Single-lead ECG was recorded at 512 Hz for subsequent HRV analysis. R-peaks were detected using a wavelet-based delineator with automatic correction. HRV features were extracted from 60-sec ECG segments, including frequency-domain indices (LF, HF, and their ratio) and nonlinear metrics from detrended fluctuation analysis ($\alpha1$, $\alpha2$). Longitudinal effects were assessed using Friedman tests with Wilcoxon signed-rank post-hoc comparisons.

Results: Significant longitudinal changes were observed during both MEM and STR tasks, whereas HRV features in resting states remained stable, indicating progressive task adaptation with reduced autonomic activation. Specifically, both cognitive tasks led to a progressive increase in vagally-mediated activity ($p < 0.01$ for HF and LF/HF), with a prominent effect in short-term variability ($p<0.01$ for $\alpha1$).

Conclusions: These findings suggest a marked association between autonomic modulation and cognitive engagement, irrespective of task type. Notably, progressive autonomic differentiation paralleled the increase in cognitive load, supporting HRV features as robust biomarkers of sustained cognitive effort with potential applications in cognitive assessment and monitoring.