A Comparative Analysis of Brain and Heart Indexes as Biomarkers of Mental Workload

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Assessing mental workload is critical for human-factors engineering. This study provides a comparative analysis for Respiratory Sinus Arrythmia (RSA), an autonomic marker of regulated effort, and the 40-Hz Auditory Steady-State Response (ASSR), a central marker of neural entrainment and cortical activity. The distinct response dynamics of each biomarker were investigated as participants performed math tasks of increasing difficulty. We found that both exhibited different sensitivity and temporal profiles, suggesting that RSA may track the slow accumulation of autonomic effort, whereas ASSR may reflect more rapid shifts in attentional gating.

Keywords: Respiratory Sinus Arrythmia, Auditory Steady-State Response, Mental Workload, Temporal Dynamics

1. Introduction

The assessment of mental workload, a critical factor in human-factors engineering, requires understanding the engagement of both the autonomic and central nervous systems as they activate mechanisms for attention and adaptation. Two prominent biomarkers in this field are Respiratory Sinus Arrhythmia (RSA), which reflects parasympathetic vagal activity tied to cognitive and emotional regulation(1), and the 40-Hz Auditory Steady-State Response (ASSR), an index of neural entrainment that captures fast cortical dynamics(2). However, while both are sensitive to overall workload, their analysis typically relies on fixed, block-average comparisons. This conventional approach obscures the crucial temporal dynamics of fatigue, adaptation, and resource depletion that unfold as a cognitive task progresses. To move beyond static snapshots, we analyzed the within-task trajectories (slopes) of RSA and ASSR. We hypothesized that cortical ASSR would show a steady decline with effort within the task, whereas autonomic RSA would follow a more complex, non-linear pattern. Differentiating these signatures is key to understanding central-autonomic interaction and building systems that can distinguish transient cognitive states from sustained overload.

2. Methods

2.1 Experimental Procedure Seven participants (all male, age range 22-24 years) took part in this study. The participants all had normal hearing and normal or corrected-to-normal vision. Participants provided informed written consent after the details of the experiment had been explained. Participants performed a mental arithmetic task in 5-minute blocks, where they summed two on-screen integers (1-49). To progressively increase mental workload across blocks, the inter-trial interval was shortened, which reduced the response window for each problem and increased the task's overall pace. The 5-minute block duration was chosen to align with short-term HRV recording standards. We recorded physiological signals at 500 Hz using a Polymate Mini system (Miyuki Giken, Japan): four EEG channels (Fpz, FCZ, FC3, FC4; left mastoid reference), single-channel ECG, and respiration from an elastic belt. The experiments in this study were reviewed by the University of Tokyo Ethics Review Expert Committee in accordance with the University of Tokyo Research Ethics Review Implementation Regulations and approved by the Dean of the Graduate School of Frontier Sciences, the University of Tokyo.

2.3 Data Analysis We derived RSA by band-pass filtering the ECG (0.5–15 Hz), detecting R-peaks, smoothing RR intervals, and mapping them onto respiration phase (via a Hilbert transform) in 0.05-cycle steps with cubic-spline interpolation; RSA amplitude was then defined as the RRI difference between inhalation and exhalation onsets(4). ASSR was indexed by the 40 Hz phase-locking index (PLI): EEG epochs were Fourier-transformed and PLI computed as in Yokota et al.(3),

$$\mathrm{PLI} = \frac{1}{n}\left|\sum_{k=1}^{n}\frac{F(f,\mathrm{ch},k)}{|F(f,\mathrm{ch},k)|}\right| \qquad (1)$$

where $F(f, ch, k)$ is the complex Fourier coefficient at frequency f from channel ch and trial k, and n is the number of trials. To capture within-block dynamics, each 5 min trial was split into two 2.5 min halves, we computed mean RSA and PLI per half and then took the z-scored slope across those two points.

3. Results

3.1 Overall Response to Workload First, both physiological signals demonstrated a clear sensitivity to workload. As task difficulty increased, mean RSA and PLI both showed a systematic pattern of decline. Participant-level correlation analysis confirmed that both biomarkers were significantly and negatively correlated with the four levels of increasing task difficulty (Table 1).

Biomarker	Simple Correlation	*p*-value
RSA	-0.85	0.020
PLI (ASSR)	-0.54	0.016

Table 1. Participant-level correlations (Fisher's z-transformed) between each biomarker and task difficulty (n=7).

3.2 Divergent Within-Trial Dynamics To assess temporal dynamics, we calculated a slope from the first to the second half of each task block, a method illustrated with data from an example participant in Fig 1.

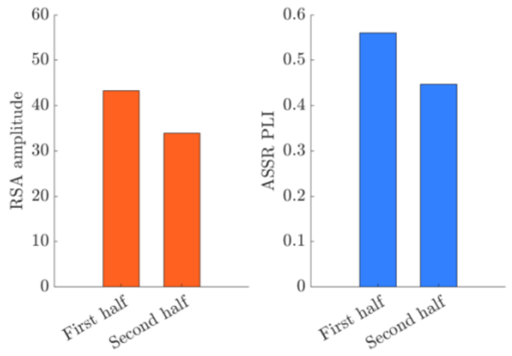

Fig. 1. Within-block changes in RSA amplitude and ASSR PLI for a single subject during one task block.

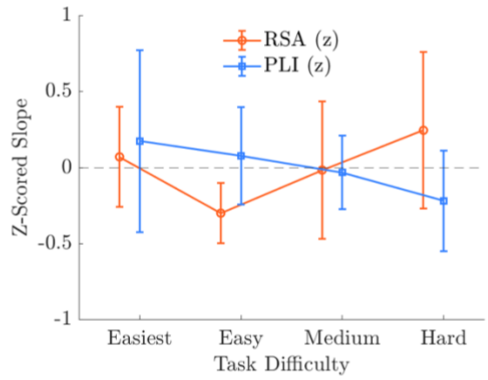

Fig. 2 The mean within-block slopes for RSA and PLI (n=7).

The within-block temporal dynamics were different for each biomarker (Fig 2). The PLI slope showed a consistent, dose-dependent negative trend as task difficulty increased. In contrast, the RSA slope followed a non-linear, U-shaped curve, becoming negative at lower difficulties before reversing to a positive slope at the highest load.

4. Discussion

The findings suggest that ASSR represent a steady depletion of attentional resources over time whereas RSA reflects a more complex, non-linear autonomic adjustment to sustained cognitive effort. Future adaptive systems could fuse ASSR's linear decline and RSA's non-linear dynamics to deliver real-time, high-fidelity workload monitoring. Future studies would benefit from a larger sample, and more precise audio triggers.

5. Acknowledgement

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