Comparative analysis of brain and heart indices as biomarkers of mental workload

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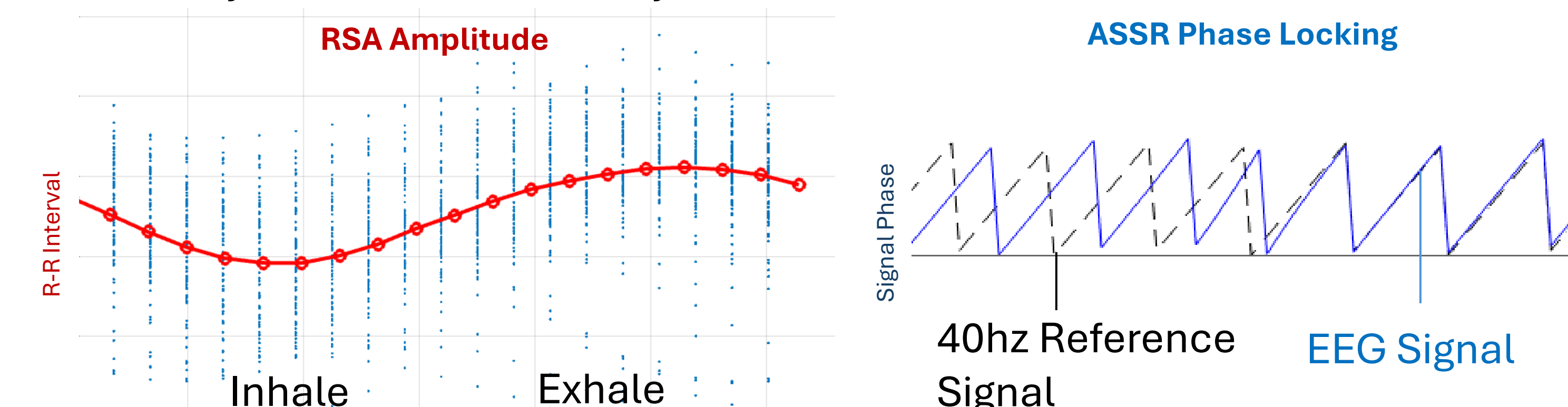(The University of Tokyo)

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Introduction

Assessing mental workload requires understanding how the autonomic and central nervous systems engage attention and adaptation. Two key biomarkers are:

- **Respiratory Sinus Arrhythmia** (RSA), reflecting parasympathetic regulation of cognition and emotion, heart rate variability's relation to breath cycle.

- **Auditory Steady-State Response** (ASSR), indexing fast cortical entrainment, the brain's synchronization to an auditory stimuli.

Hypothesis: ASSR would steadily decline with task effort, while RSA would follow a more complex, non-linear trajectory.

- Distinguishing these indices' role in central–autonomic interaction is vital to designing systems with transient cognitive states from sustained overload.

Methods

- Seven males (22-24 yrs), normal hearing/vision, gave informed consent
- Mental arithmetic in 5-min blocks: sum of two on-screen integers from 1-49
- Workload increased by shortening inter-trial interval; increased answer pace by reducing response window.

Fig. 1 Task procedure. Each task is done in 5-min blocks, two step mental arithmetic problems are as follows: 12+39 = x?, then x 10s place + x 1s place = ?.

- Recording was done using 500 Hz sampling with Polymate Mini (Miyuki Giken, Japan).
- EEG channels: FPZ, FCZ, FC3, FC4 (referenced to left mastoid).
- ECG + Respiration recorded via elastic belt.

- RSA derived by bandpass 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.
- ASSR was indexed by the 40 Hz phase-locking index (PLI): EEG epochs were Fourier-transformed and PLI computed using the equation for inter-trial phase coherence,

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

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.
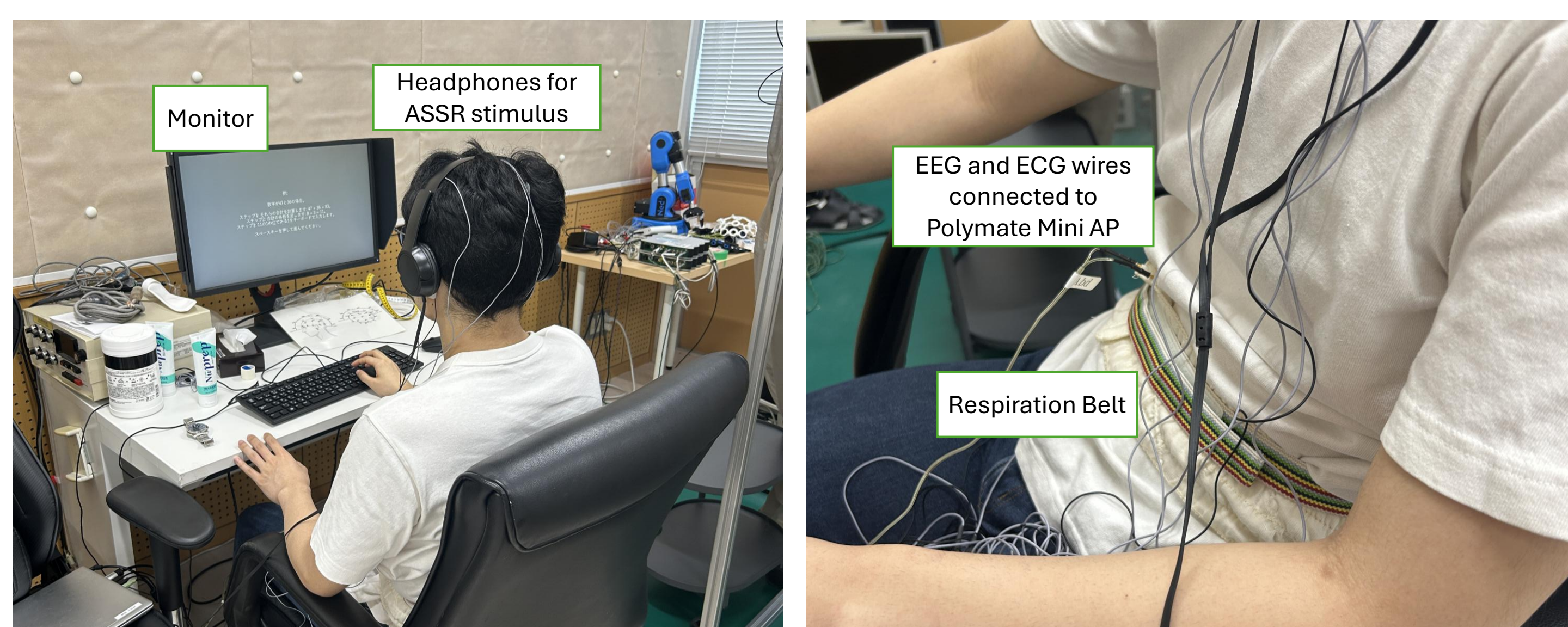

Fig. 2 Picture of the recording method and equipment used. Biomarker acquisition was done with the Polymate Mini AP108.

Results

- **Validation of both RSA & PLI** achieved by showing sensitivity to workload.
- Increasing task difficulty correlated with systematic declines in mean RSA and PLI
- Participant-level correlations confirmed **significant negative relationships** between both biomarkers and four difficulty levels (Table 1). Results validate RSA and ASSR (PLI) as reliable indices of mental workload

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

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

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 3.
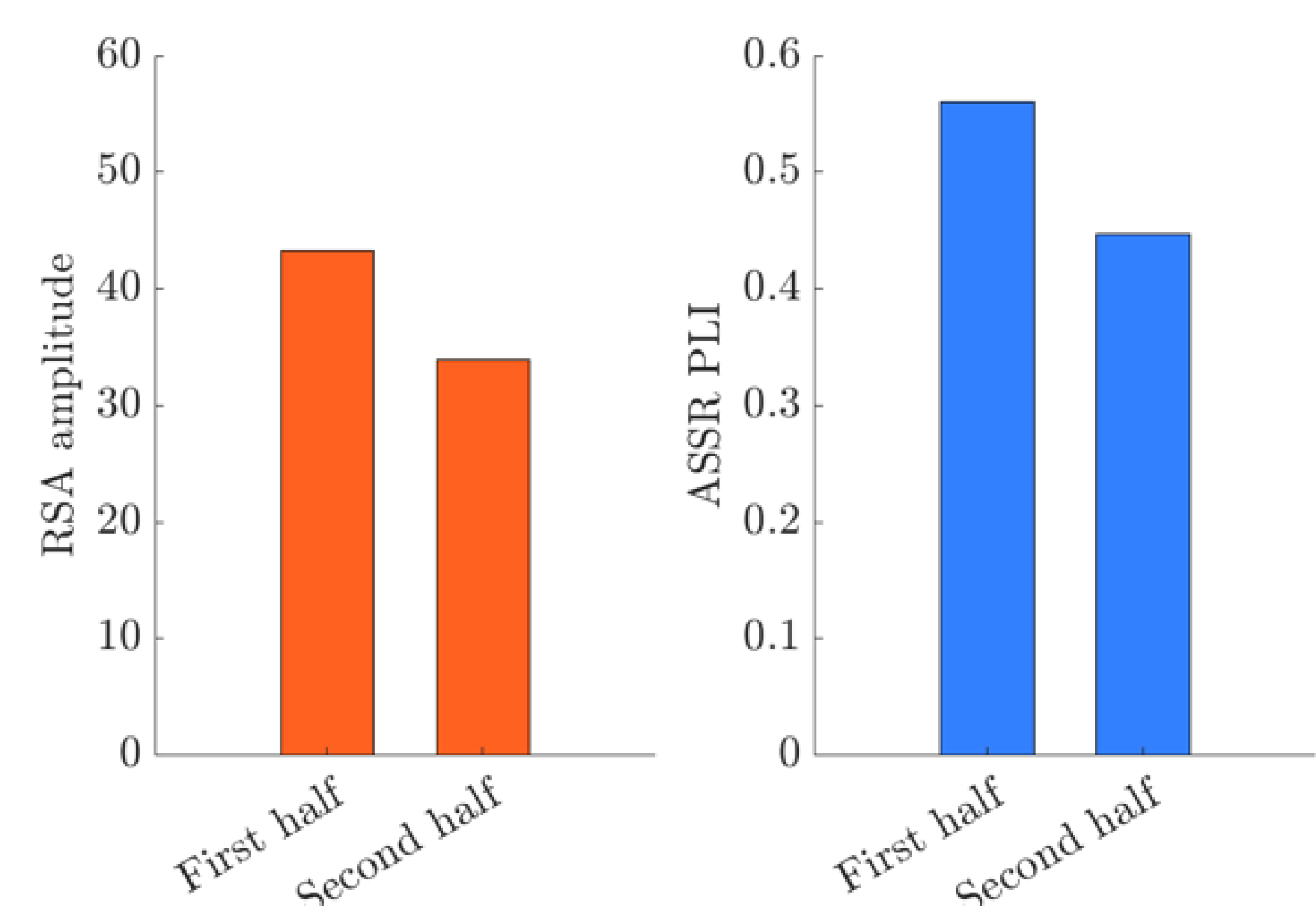

Fig. 3 Within-block changes in RSA amplitude and ASSR PLI for a single subject during one task block.
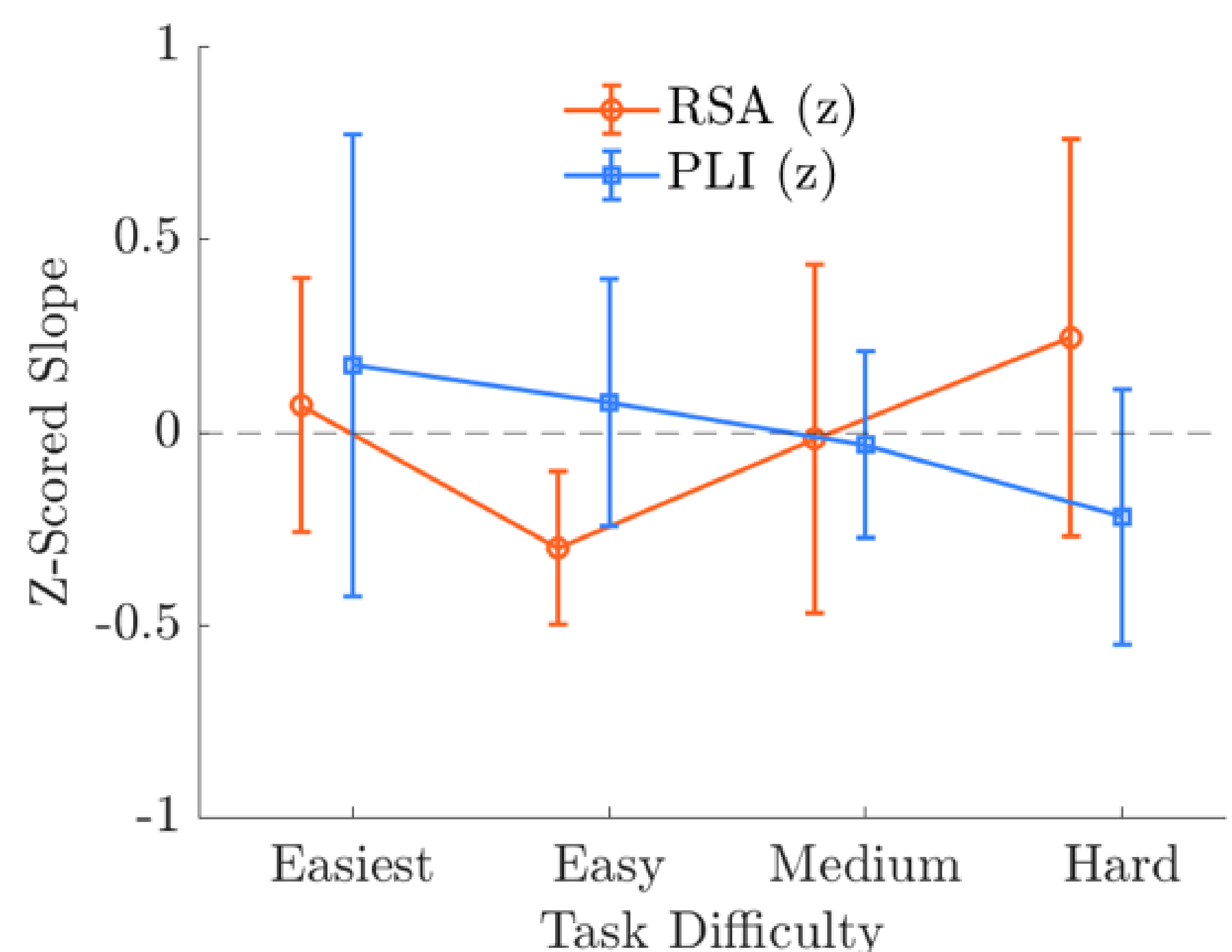

Fig. 4 The mean within-block slopes for RSA and PLI (n=7).

As hypothesized biomarker within-block temporal dynamics differed (Fig 4):
- PLI slope showed consistent, dose-dependent **linear negative trend** as task difficulty increased.
- RSA slope followed a **non-linear, U-shaped curve**, becoming negative at lower difficulties before reversing to a positive slope at the highest load.

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 larger sample; more precise audio triggers.

Acknowledgement