Multi-way Data Analysis for Advanced Physiological Estimation of Cognitive Status

Roman Rosipal

Department of Theoretical Methods
Institute of Measurement Science, SAS
Bratislava, Slovak Republic
&
Pacific Development and Technology, LLC
Palo Alto, CA

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Estimation of Cognitive Status

Behavior and Performance

- Aroused or Overloaded
- Working
- Fatigued
- Engaged
- Resting
- Other States

Internal Processes

- Reward system
- Autonomic system
- Executive control
- Sensation & perception
- Working memory
- Other Processes

Biosignals

Models and Algorithms
**Useful Definitions**

- **Engagement**: selection of a task as the focus of attention and effort

![Diagram showing the relationship between Engagement, General Cognitive Status, Workload, Mental Fatigue, and Non-specific Factors.](image)
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- **Workload**: significant commitment of attention and effort to task
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- **Engagement**: selection of a task as the focus of attention and effort
- **Workload**: significant commitment of attention and effort to task
- **Overload**: task demands outstrip performance capacity
- **Mental Fatigue**: desire to withdraw attention and effort from a task
Why to monitor cognitive status?

- Critical safety, high workload, stressful, etc., environments
Experiments - (A) Cognitive Workload Monitoring

- Uninhabited Air Vehicle (UAV) control
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- Trained subjects were monitoring several UAVs as they flew a preplanned mission; processing SAR images (synthetic aperture radar), vehicle health control, etc.
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- Trained subjects were monitoring several UAVs as they flew a preplanned mission; processing SAR images (synthetic aperture radar), vehicle health control, etc.

- Different task conditions were used to control cognitive workload levels
Experiments - (B) Mental Fatigue Monitoring

- Continuous performance of mental arithmetic for up to three hours
Cerebral Cortex
- the outermost layers of brain
- 2-4 mm thick (human)

Structure of a Typical Neuron
Data - EEG Sources
Data - Multi-modal Multi-Sensor

- ECG - hear rate, heart rate variability
- EOG and eyes control - hEOG, vEOG movements, blinks, pupil diameter
- EMG
- Skin conductance, SCR, GCR
- Videotaped recordings
- Response time, Correctness of responses
- Subjective responses and questionnaires
- etc.
Spectral EEG Data Representation

- Data were segmented into epochs (usually 2 sec long)
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- **Spectral representation**: Thompson multitaper estimate of the power spectrum density; that is the distribution of power per unit frequency

\[ P_{xx}(f) = F_x(f)F_x^*(f) \]

where \( F_x(f) \) is the Fourier transform of the signal \( x \) and \( * \) indicates the complex conjugate
Spectral EEG Data Representation

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- **Spectral representation**: Thompson multitaper estimate of the power spectrum density; that is the distribution of power per unit frequency

\[ P_{xx}(f) = F_x(f)F^*_x(f) \]

where \( F_x \) indicates
- **Example:**

![An example of the power spectral density estimate
Subject B, electrode Cz](image-url)
Coherence EEG Data Representation

- **Coherence representation:** Cross power spectra density $P_{xy}(f)$,

$$P_{xy}(f) = F_x(f)F_y^*(f)$$

or magnitude squared (coherence)

$$C_{xy}(f) = \frac{|P_{xy}(f)|^2}{P_{xx}(f)P_{yy}(f)}$$
Data Structure

- **Data matrix construction:** \( X(I \times J \times K) \)
  - \( I \) - time segments
  - \( J \) - electrodes or electrode pairs
  - \( K \) - PSD or CSD (coherences)
Bilinear Unfolding

- Representing all experimental factors in one dimension & observations (trials) in second dimension
- Contrast each dimension vs. pair of the other two
Bilinear Unfolding - Modelling

Factor Analysis

\[ x_{ij} = \sum_{f=1}^{F} a_{if} b_{jf} + e_{ij} \]

Principal Component Analysis (PCA)

\[ e_{ij} = 0 \]
Partial Least Squares

- **Data sets:**
  \[ X (n_{\text{objects}} \times N_{\text{variables}}) \]
  \[ Y (n_{\text{objects}} \times M_{\text{responses}}) \]

- **Bilinear decomposition:**
  \[ X = TP^T + E \]
  \[ Y = UQ^T + F \]
  where:
  - \( T,U \): matrices of score vectors (LV, components)
  - \( P,Q \): matrices of loadings
  - \( E,F \): matrices of residuals (errors)

- **Criterion:**
  \[ \max_{|r| = |s| = 1} [\text{cov}(Xr, Ys)]^2 = [\text{cov}(Xw, Yc)]^2 \]
  \[ = \text{var}(Xw)[\text{corr}(Xw, Yc)]^2 \text{var}(Yc) \]
  \[ = [\text{cov}(t,u)]^2 \]
Bilinear Unfolding - (Kernel) PLS - Classification
Multi-way Analysis

PARAFAC

\[ x_{ijk} = \sum_{f=1}^{F} a_{if} b_{jf} c_{kf} + e_{ijk} \]
PARAFAC model

- **The PARAFAC model with \( F \) factors:** decomposition of the data matrix \( X \) using three loading matrices, \( A, B, \) and \( C \) with elements \( a_{if}, b_{jf}, \) and \( c_{kf} \)

\[
x_{ijk} = \sum_{f=1}^{F} a_{if} b_{jf} c_{kf} + \epsilon_{ijk}
\]

- **The criterion:**

\[
\min_{a_{if}, b_{jf}, c_{kf}} = \| x_{ijk} - \sum_{f=1}^{F} a_{if} b_{jf} c_{kf} \|^2
\]
Multi-way PLS

Multi-way PLS (n-PLS)

Software: proprietary m-codes developed by PDT, LLC, and subroutines from the N-way toolbox for Matlab (Andersson and Bro, 2000)
Mental Fatigue - PLS analysis

**Black = Alert**  **Red = Mentally Fatigued**

- **Fz**
- **Pz**
- **Frontal**
- **Theta**
- **Parietal**
- **Alpha**

**Power (µV²/Hz)**

**Frequency (Hz)**

![Graph showing brainwave analysis](image)

- **KPLS Component 1 vs KPLS Component 2**
  - Last 15 min
  - 1st 15 min

- **Kernal Partial Least Squares Score**
  - Alert
  - Normal
  - Fatigued

- **Epoch**
  - Alert
  - Normal
  - Fatigued

**Introduction**

**Methods**

**Results**

**Conclusions**
Mental Fatigue - PLS analysis
Robust EEG-Based Classification of Mental Fatigue

<table>
<thead>
<tr>
<th>Signal-to-noise Ratio (dB)</th>
<th>Test Proportion Correct</th>
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<tr>
<td>-18</td>
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<tr>
<td>-15</td>
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<tr>
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<td>-3</td>
<td>99</td>
</tr>
<tr>
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<td>100</td>
</tr>
</tbody>
</table>

- 21 Channels: 50, 56, 79, 94, 99, 100, 100
- 12 Channels: 50, 51, 65, 88, 96, 98, 98
- 4 Channels: 50, 54, 76, 88, 90, 88, 87

Robust EEG-Based Classification of Mental Fatigue

2300 (Day 1) vs. 1900 Hrs (Day 2)
Figure 33. Atomic decomposition of EEG from participant GSD of the NASA-C study. EEG recordings from 30 channels were processed using PARAFAC decomposition to yield a model consisting of four atoms, each have dimensions of space (electrodes), frequency (power spectral density) and time (time on task). Graphical conventions are the same as in Figure 32. This participant performed the task for three hours, or 12 15-minute blocks. The time axis measures seconds as multiples of 2-second long EEG epochs which were not all contiguous, due to rejection of EEG segments containing movement or other artifacts. Some blocks have fewer epochs than others because the incidence of EEG artifacts increased during those blocks.
Figure 45. Coherence analyses for participant GSD. Graphing conventions are explained in Figure 44.
Subjects E,G,I, K (plotted subject E)
Subjects E - coherence

- 1. atom
- 2. atom
- 3. atom

Details of atom2
Subjects E - coherence

We found the similar decomposition for subjects B, G, I, K
Subjects B, E, G, I, K - coherence
Workload - UAV - Coherence Analysis

![Graph showing coherence analysis results for different factors and subjects.](image-url)
Results show that mental workload may be tracked by EEG components isolated using PARAFAC.

On UAV data set, the workload related atoms was remarkably stable in 5 out of the 6 subjects.

The short-and long range coherence related atoms are more stable across the subjects, provide higher discrimination of the low and high workload levels and seem to be less susceptible to the movement related artifacts.

We observed similarly promising and remarkable results on additional two data sets monitoring cognitive status.
Detailed Results

http://www.um.savba.sk

References:

Work carried out with:

Leonard J Trejo & Paul Nunez

Thank you !!!