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Ocular artefact removal from multi-channel EEG data with tensor decomposition

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Abstract

Removing the effect of ocular artefacts in electroencephalogram (EEG) analysis is an essential preprocessing step. In addition to traditional approaches such as ICA and regression-based algorithms, tensor decomposition methods are receiving increasing attention in ocular correction. Within this approach, a multichannel EEG signal, represented by a tensor, is decomposed into a set of latent components. After identifying and removing components representing ocular activity, the cleaned tensor is transformed into the time-space domain. This study focuses on three component removal algorithms from EEG tensors. These approaches are compared theoretically and when applied to real eye-blink corrupted EEG data under the assumption of component nonnegativity.

Introduction

The concept of using tensor decomposition for ocular correction of EEG signals is not new [1, 2]. Removing eye-blink related latent components is a crucial step of the algorithm. In this study we aim to identify an optimal approach for component removal in the process of EEG ocular correction with tensor decomposition under the assumption of component nonnegativity.

Data

- EEG measurement during meditation with opened eyes of a Himalayan monk
- electrodes - Fp1, F3, F7, C3, T7, P3, P7, O1, Pz, Fp2, Fz, F4, F8, Cz, C4, T8, P4, P8, O2
- high-pass (cutoff freq. 0.5 Hz) and low-pass (cutoff freq. 30 Hz) filter

Artefact removal with tensor decomposition

1. EEG tensor $\underline{\boldsymbol{X}} \in \mathbb{R}_+^{I \times J \times K}$ construction
   - EEG signal from J electrodes is divided into I overlapping windows
   - spectrum over K frequncies for each time window
2. tensor decomposition - Parallel factor analysis (PARAFAC) [3]
   - nonnegativity constraints in the temporal, spatial and frequency mode

$$\underline{\boldsymbol{X}} = \underline{\boldsymbol{\Lambda}} \times_1 \boldsymbol{A} \times_2 \boldsymbol{B} \times_3 \boldsymbol{C} + \underline{\boldsymbol{E}} = \sum_{f=1}^{F} \lambda_f \mathrm{a}_f \circ \mathrm{b}_f \circ \mathrm{c}_f + \underline{\boldsymbol{E}}$$

3. eye-blink component selection and removal
4. transformation of the tensor $\underline{\boldsymbol{X}}_{clean}$ from the time-space-frequency domain into the time-space domain (for example by ADMMGLA [4])

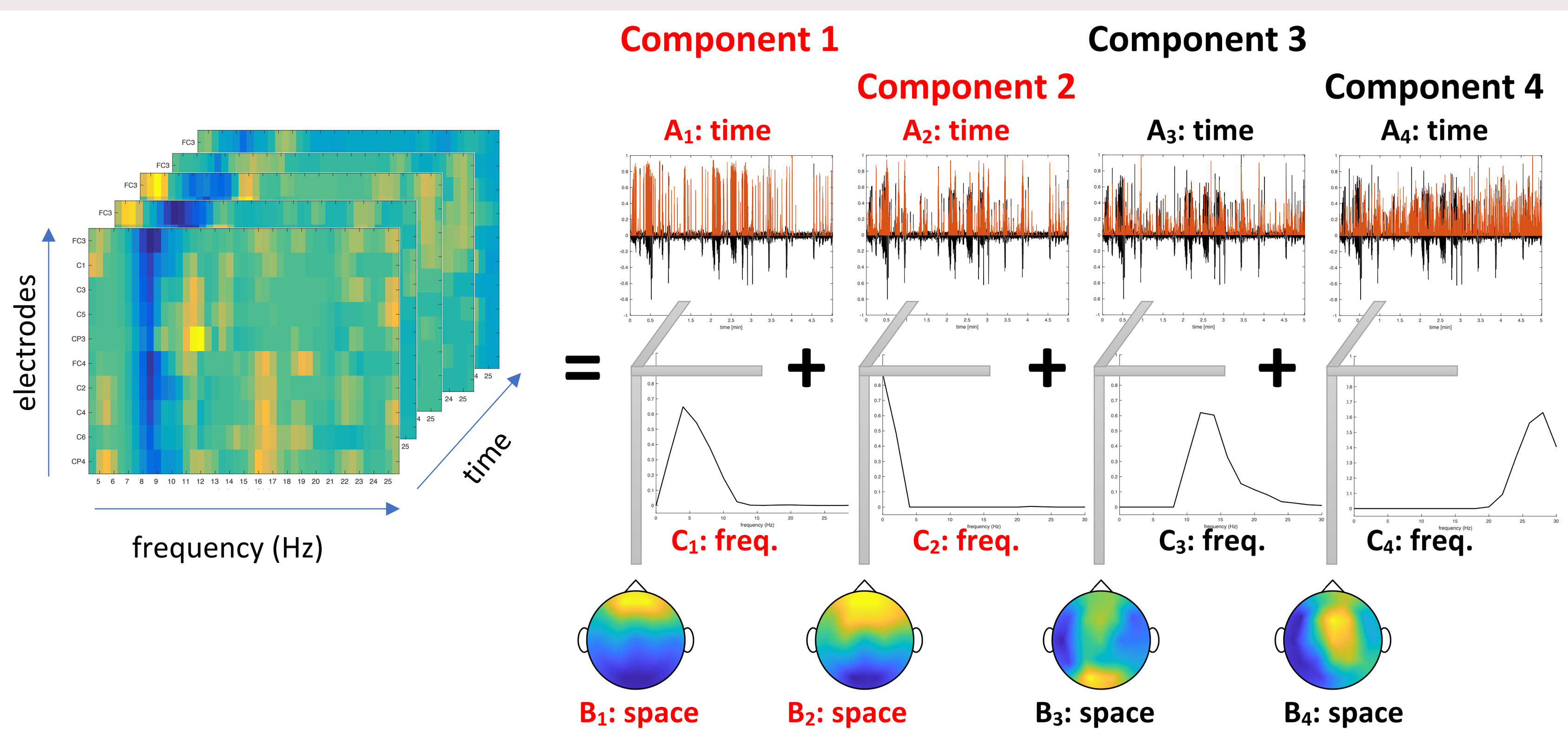

Figure: Graphical schema of the Parallel factor analysis (PARAFAC) decomposition of EEG signal corrupted by eye blinks - the frequency signatures ($\boldsymbol{C}_i, i = 1 \ldots, 4$), time scores ($\boldsymbol{A}_i, i = 1, \ldots, 4$, orange), and spatial signatures ($\boldsymbol{B}_i, i = 1, \ldots, 4$) of four PARAFAC components. Time scores are depicted together with the original EEG signal from the Fp1 electrode (black). Two components representing eye-blinks and selected for removal are highlighted in red.

Eye-blink component removal from the EEG tensor

- $\boldsymbol{S}_{rem}$ = index set of eye-blink related components to remove

1. **component zeroing** [5]

$$\underline{\boldsymbol{X}}_{clean} = \sum_{f=1}^{F} \lambda_f \mathrm{a}_f^\star \circ \mathrm{b}_f^\star \circ \mathrm{c}_f^\star = \sum_{f \notin S_{rem}} \lambda_f \mathrm{a}_f \circ \mathrm{b}_f \circ \mathrm{c}_f$$

$$\mathrm{a}_f^\star = \begin{cases} \mathrm{a}_f, f \notin S_{rem}, \\ 0, f \in S_{rem}, \end{cases} \quad \mathrm{b}_f^\star = \begin{cases} \mathrm{b}_f, f \notin S_{rem}, \\ 0, f \in S_{rem}, \end{cases} \quad \mathrm{c}_f^\star = \begin{cases} \mathrm{c}_f, f \notin S_{rem}, \\ 0, f \in S_{rem}, \end{cases}$$

2. **component subtraction**

$$\underline{\boldsymbol{X}}_{clean} = \underline{\boldsymbol{X}} - \sum_{f \in S_{rem}} \lambda_f \mathrm{a}_f \circ \mathrm{b}_f \circ \mathrm{c}_f = \sum_{f \notin S_{rem}} \lambda_f \mathrm{a}_f \circ \mathrm{b}_f \circ \mathrm{c}_f + \underline{\boldsymbol{E}}.$$

3. **projection onto a nullspace of the n^{th}-mode signature subspace ($\boldsymbol{Proj}_n$)** [2]

$$\underline{\boldsymbol{X}}_{clean} = \underline{\boldsymbol{X}} \times_n P_n, \qquad P_n = \mathbb{I}_{J_n} - \boldsymbol{M}^{(n)} \boldsymbol{M}^{(n)+}$$

$$\text{for example } \boldsymbol{M}^{(1)} = (\mathrm{a}_{f_1}, \ldots, \mathrm{a}_{f_M}), \qquad S_{rem} = \{f_1, \ldots, f_M\}$$

Results

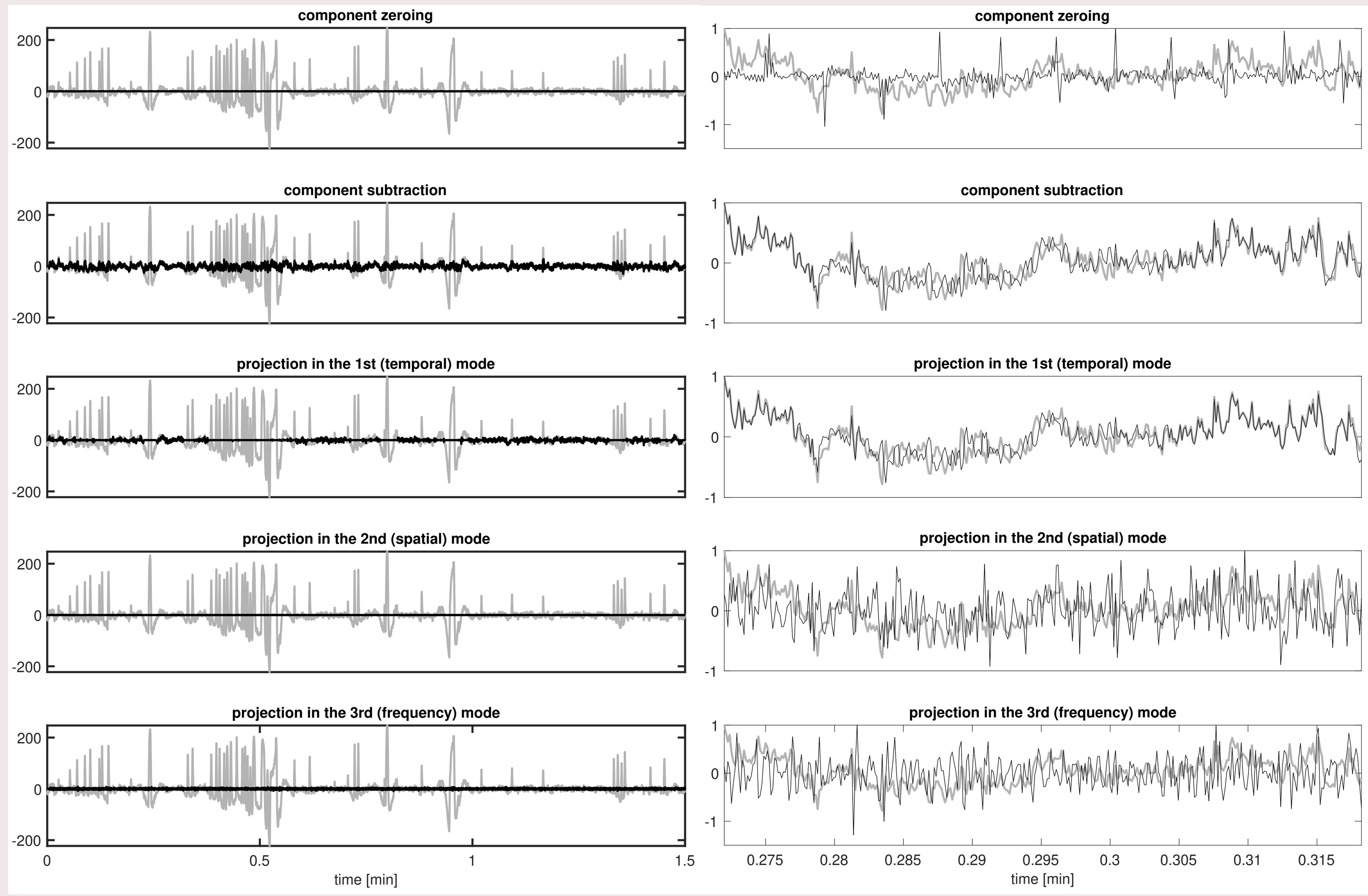

Figure: Left: The eye-blink contaminated EEG signal (grey) from the Fp1 electrode and reconstructed signal (black) with i) component zeroing, ii) component subtraction, iii) $\boldsymbol{Proj}_1$ iv) $\boldsymbol{Proj}_2$, or v) $\boldsymbol{Proj}_3$. Right: Comparison of normalised original and reconstructed signal on a short time interval with any visible eye-blink.

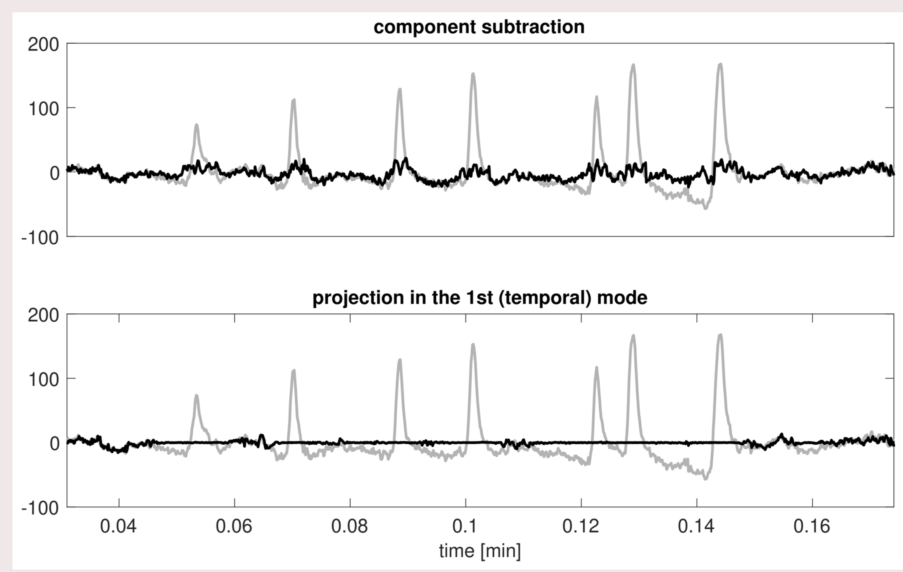

Figure: Normalised original and reconstructed EEG signal on a time interval with eye-blinks.

Conclusions

- In the case of **component zeroing**, $\boldsymbol{Proj}_2$ and $\boldsymbol{Proj}_3$, the reconstructed EEG signal followed a close-to-zero line. Moreover, all three approaches produced changes in the EEG signal profile also on non-blink time intervals.
- When considering $\boldsymbol{Proj}_1$, the original and reconstructed signal overlapped over non-blink time intervals and eye blinks were successfully removed. However, $\boldsymbol{Proj}_1$ replaced detected eye blinks with a close-to-zero line.
- When using **component subtraction**, the reconstructed signal followed visually the most realistic EEG signal properties.
- Therefore, we can conclude that only **component subtraction** is appropriate component removal method in EEG ocular correction with tensor decomposition. Nevertheless, further validation and experiments are needed.

References

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