The power of Tensor algebra in medical diagnosis

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• Introduction
  • EEG and epileptic seizure monitoring
  • Blind Source Separation
• Tensor Algorithms
• Examples in EEG monitoring
• Conclusions and new directions
### Introduction: EEG and epileptic seizure monitoring

<table>
<thead>
<tr>
<th>Interictal EEG</th>
<th>Ictal EEG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spikes, slow waves (epileptiform activity?)</td>
<td>Ictal source localization</td>
</tr>
</tbody>
</table>

#### 21 electrode positions @UZ Gasthuisberg
Blind source separation

EEG analysis difficult because of artefacts → REMOVE

Matrix based Blind Source Separation (BSS) → Constraints!

- sources orthogonal (PCA),
- statistically independent (ICA)
- sources uncorrelated and of different autocorrelation (CCA)

$$\text{EEG}_1 = a_{11}s_1 + a_{12}s_2 + a_{13}s_3$$
$$\text{EEG}_2 = a_{21}s_1 + a_{22}s_2 + a_{23}s_3$$
$$\text{EEG}_3 = a_{31}s_1 + a_{32}s_2 + a_{33}s_3$$

$$\text{EEG} = A.s$$
• Introduction
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Tensor Algorithms: Canonical Decomposition (PARAFAC)

- Advantage for BSS: Tensor Decompositions unique under mild conditions!
- Overviews: P. Comon (talk and papers), Kolda & Bader (SIAM Rev. 2009)
- PARAFAC -> Decomposition into minimal number of (non)orthogonal rank 1 tensors
  - compute via alternating least squares (Smilde, Bro, and Geladi, 2004) → most popular
  - Simultaneous matrix diagonalization/ generalized Schur (De Lathauwer, 2004, 2006)
  - Other schemes (Paatero, 1999; Vorobyov, Sidiropoulos and Gerschman, 2005, …)
  - With orthogonality constraints (Kolda, 2001; Zhang and Golub, 2001)
  - Online PARAFAC (Nion and Sidiropoulos, 2009)
  - Matrix-free Nonlinear Least Squares using Levenberg-Marquardt (Sorber et al., 2012)
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  – Neonatal seizure localization
  – Event-Related Potential analysis
• Conclusions and new directions
Split EEG in different frequencies using wavelets.

\[ Y = A_1 B_1 C_1 + \ldots + A_R B_R C_R + E \]

PARAFAC for seizure onset localization

=> Analysis in 3 dimensions instead of just 2
PARAFAC: Example extracting 1 component

\[ X = A_1 \times B_1 \times C_1 \]

- \( B_1 \): time course
- \( A_1 \): distribution over channels
- \( C_1 \): frequency content (distribution across scales).

**Interpretation of a trilinear component**
PARAFAC for seizure onset localization

\[ \chi = \mathbf{A}_1 \mathbf{B}_1 + \ldots + \mathbf{A}_R \mathbf{B}_R + \mathbf{E} \]
Reconstructed epileptic atom

(De Vos et al., NeuroImage 2007) (E. Acar et al, Bioinformatics 2007)
More interesting seizure
More interesting seizure
• Muscle artifacts are distributed over frequencies by wavelet transformation and cannot be modeled by a trilinear structure

• In 2 (or 10) seconds, seizures are stable in time, frequency and space

• PARAFAC is "unique"
Validation study with UZ Leuven → ictal EEG of 37 patients
• Visual analysis: 21 well localized
• New method: 34 well localized

PARAFAC:
→ separates ictal atom from background EEG
→ is more reliable than visual analysis and matrix techniques (ICA, SVD) for seizure onset localization
→ can be used as preprocessing step for source localization
Limits of a trilinear model

• A sinusoidal signal gives rise to a perfect trilinear model after wavelet transforming,

• But what happens if the frequency changes during the analyzed time interval?

• We simulated a chirp, added noise and localised the epileptic EEG
Limits of a trilinear model

- Signal is not perfectly recovered (as expected)
- But it is still well localized!
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Lack of oxygen supply leads to brain damage

The occurrence of seizures best indicator for neurological damage and can increase damage if not properly treated

Most seizures subclinical (90%): only detectable via EEG monitoring.

→Need for automated EEG monitoring.
Collaboration with Sophia Child Hospital, Rotterdam, NL

In the USA:
• 1 on 8 births premature
• 11.1% of prematures have seizures
Algorithm, mimicking the human observer: 
*(Deburchgraeve et al., Clinical Neurophysiology 2008 & 2009)*

2 seizure types:

- **Spike train**
- **Oscillation**
- **Combination**

For each type a separate detection algorithm was developed.
Seizure on C3-Cz-F3 + artefact on T5

⇒ O-CP: Extract spatial distribution of the seizure without distortion of the artifact.
Extract & localize oscillations using PARAFAC

A

B-components CP-decomposition

B

(1) (2)

(1) (2)
PARAFAC models as much variance as possible in the tensor that fits in a trilinear structure.

⇒ Sensitive for activity that is active during the whole time segment, stable in localization and frequency

\[
\begin{array}{c}
X \\
\end{array}
\begin{array}{c}
A_1 \\
B_1 \\
C_1
\end{array}
\]

⇒ Oscillations in the EEG meet those requirements, thus PARAFAC is most sensitive for oscillations in the EEG.

⇒ *Less suitable for spike train type seizures* as they are discontinuous and too local in time.
Extract & localize spikes using PARAFAC

We use the output of the seizure detector:
Construction of the tensor:

Spikes detected by seizure detector

\[ \text{EEG} \]

Add the EEG segments to the tensor

\[ A + B = C \]

\[ E \]
Extract & localize spikes using PARAFAC

SP-CP:

\[
\begin{align*}
\text{Distribution over the detected spikes} \\
\text{Amplitude} \\
\end{align*}
\]
Comparison with spike averaging
- Construct tensor with 20 identical EEG spike segments
- Add random noise to the tensor with different SNR
- Calculate correlation with the noise free spatial distribution

![Impact of noise on the localization](chart.png)
Comparison with visual analysis of the EEG by a neurophysiologist.

- In all cases there is a good qualitative correspondence between the neurologist and the algorithm.

- Localization plots are helpful tool for neurophysiologist in analyzing seizures.

- Together with seizure detector: useful for brain monitoring at the bedside.
PARAFAC expects a fixed localization in time:

- Divide migrating seizures into smaller windows

Long seizures >1min:

- Divide into smaller windows

**Current research:**

- PARAFAC useful to delineate ictal onset zone?
  1. use the extracted spatial distribution as *input to dipole source localization* with a realistic head model
  2. *using simultaneous EEG-fMRI: prospective validation* in the presurgical work-up for epilepsy surgery.
• Blind source separation
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• **Examples in EEG monitoring**
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Tasks during data acquisition

EEG with 62 electrodes+EOG+ECG in 3T
Variable randomized SOA

1. Detection task
2. Go/NoGo task
EEG analysis 1: average ERPs

EEG measured at Pz electrode

Average of 20 Os

Average of 80 Go
ERPs have very low SNR and suffer from artifacts caused by non-brain and brain sources

**Variety of PARAFAC Applications, e.g.:**

- Brain topography *(Field and Graupe, *Brain Topogr.* 1991)*

- Brain-computer interfacing *(A. Cichocki, *IEEE computer society magazine*, 2008)*


- Inter-trial phase coherence analysis in event-related EEG *(Mørup et al., *NeuroImage* 2005) *(M. Weiss et al., *ICASSP* 2009)*

- Event-related EEG (during simultaneous fMRI acquisition)
Application of PARAFAC to Event-Related EEG allows
– including three or more data dimensions into the tensor for ERP analysis (e.g. subjects, trials, tasks, etc.)
– unique data decomposition without additional assumptions
– finding ERP properties not revealed by traditional averaging

Preprocessing important, e.g.
• removal of artifacts
• Imposing orthogonality in 1 mode (trial, subject) to avoid degeneracy
• Optimize parameters (number of components between 2 and 10)
ERP analysis: PARAFAC on channels $x$ time $x$ trials

$$X = \sum_{r=1}^{R} C_r B_r^T + E$$
PARAFAC on Channels x Time x Subjects ERP for upper right stimulus

Recorded in scanner plus fMRI
Averaged ERPs per subject
→ 5 left occipital channels
→ different P1 latencies found
  in grand average ERP
  separated in 2 components

Recorded in scanner, no fMRI
Averaged ERPs per subject
→ all channels
→ 2 components: grand average (left) and BCG artefact (right)
Validation: classification of trial type

Left vs. right stimuli

• **Raw data**: based on difference in P1 amplitude (left – right)
• **PARAFAC**: based on 1 trial mode of decomposition
• In both cases: $\frac{1}{2}$ trials for training, $\frac{1}{2}$ for testing
Quadrant stimuli

- **Raw data**: based on P1 left-right difference and C1 amplitude
- **PARAFAC**: based on 2 trial modes of decomposition
- In both cases: ½ trials for training, ½ for testing
• PARAFAC allows the extraction of task-related ERP information on a single trial basis
• Performance is better than raw data characteristics
• Both for left-right and 4 quadrant distinction
• More difficult but still possible for simultaneously acquired EEG data

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Conclusions: Tensors increasingly popular in biom. SP

- Successful: e.g. epileptic seizure onset localization using multichannel EEG
- Mostly restricted to PARAFAC via alternating least squares
- PARAFAC more sensitive than visual EEG reading for seizure localization
- Electrode artifacts disturb localization …
- PARAFAC output used as starting point for 3D EEG source localization
- Remark: Tucker3 model has also been used for seizure localization (Acar et al., IASTED 2007)

Future challenges?
Block Tensor Decomposition

\[ \mathbf{X} = \mathbf{A}_1 \mathbf{S}_1 \mathbf{B}_1 + \ldots + \mathbf{A}_R \mathbf{S}_R \mathbf{B}_R \]

Ref: De Lathauwer et al., SIMAX, 2008; Sorber et al., SIOPT, 2012
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iMinds CONNECT.INNOVATECREATE
Thank you for your attention!

Questions?

http://www.esat.kuleuven.be/scd/