Detection of synchronization in single brain signals

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10/23/06
1. Problems and solutions in data analysis
   - Problems
   - Standard solutions

2. Mutual synchronization
   - Motivation
   - The method
   - Application to ERPs
   - Application to MAEPs

3. Mutual phase synchronization
   - Basic ideas
   - Application

4. Outlook
1 Problems and solutions in data analysis
   - Problems
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4. Outlook
Analysis approaches

- **top-down approach:**
  data analysis extracts properties of underlying neural activity
  → this talk

- **bottom-up approach:**
  mathematical neural modeling aims for the understanding of experimental results

(binding problem)
Some problems in the top-down approach

- high variability in measured signals in experimental trials
- in cognitive experiments:
  - markers of cognitive neural processes in experimental data
  - how to reduce complexity of data, e.g.
    - high dimensionality of data
    - fast transient processes
    - outlier detection
    - external and internal noise
- inverse problem → hypothesis necessary
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Aim A: find activity of underlying physiological process by averaging

Hypothesis of event-related activity:

- before stimulus: physiol(t) = 0
- after stimulus:
  measurement (t) = physiol(stimulus(t)) + noise (t)
- averaging: <measurement (t)> = physiol(stimulus(t))
- averaging valid for large number of trials

however:

- Tass, Arieli et al: stimulus changes ongoing activity
  physiol(t) = physiol(stimulus(t), noise (t))
- no optimal approach for small number of trials
Outlier detection

Aim B: increase quality of statistics by removal of trial outliers

- methods for clear identifiable artifacts:
  - Independant Component Analysis
  - eye-tracker
  - blinking of the eyes
  - artifacts based on behavioral data

- however: internal artifacts, as missing attention during task or habituation effects are difficult to detect
Idea to solve some problems

Study of single trials and subsequent statistic of results on single trials

- Advantage:
  - A: statistics of small number of trials as data already denoised
  - A: possible treatment of different hypothesis’
  - B: improved detection of internal outliers

- problem: criterion for underlying process in noisy signal

- solution: detection of mutual behavior of multivariate signals
  - analysis of signal itself
  - analysis of the signals amplitude or its phase
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Visual classification task


- Task: count silently the occurrences of Kanizsa-square figures
- EEG with 64 electrodes, sampling rate 500 Hz
- 20 subjects, 400 stimuli, equal appearance probability
- Measurement during first 700ms after stimulus presentation
- Random inter-stimulus interval between 1000ms and 1500ms
Results

subject average of target activity

analysis task: extraction of ERP-components
Problems and solutions in data analysis

Mutual synchronization

Mutual phase synchronization

Outlook

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Application to ERPs

Application to MAEPs

Clustering

Data windows of ERP-components show mutual behavior in most channels and represent agglomerations of data points


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Clustering results

(Int. J. Bif. Chaos 2004)
Detecting synchronization in single brain signals

Clustering results

- **Motivation**
- **The method**
- **Application to ERPs**
- **Application to MAEPs**

Problems and solutions in data analysis

Mutual synchronization

Mutual phase synchronization

Outlook

**Clustering results**

![Graph showing Euclidean distance over time with clusters labeled 1 to 6.](chart.png)

- **Cluster 1**
- **Cluster 2**
- **Cluster 3**
- **Cluster 4**
- **Cluster 5**
- **Cluster 6**

**Time [ms]**

- 0
- 200
- 400
- 600

**Euclidean distance**

- 0
- 20
- 40
- 60
- 80
- 100

(Int. J. Bif. Chaos 2004)
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Detection of synchronization in single brain signals
Auditory middle-latent evoked potentials

Experiment:
- subject hears a click tone of length 100 µs, average over $10^4$ trials
- EEG recorded with 32 channels from three subjects
Clustering results

(Physica D 2003)

extension of Principal Component Analysis by synchronous model fit

minimizing

\[
V = V_{PCA}(w_i, q) + \epsilon V_d(f, w_i, q)
\]

yields

\[
y_i = q w_i, \quad \dot{y}_i = f_i(y_j)
\]

with

\[
f_i(y_j) = a_i + b_{i1} y_1 + b_{i2} y_2 + c_{i1} y_1^2 + c_{i2} y_1 y_2 + \ldots
\]
Low-dimensional model

Detection of synchronization in single brain signals

(Physica D 2003)
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Importance

- in-phase synchronization between
  - hemispheres (Engel et al., Science (1991))
  - cortex, LGN and retina (Castelo-Branco et al., J.Neurosc. (1998))
  - visual areas (Bressler, Beh. Brain. Res. (1996))
- possible solution for binding problem
- mechanism of evoked response:
  - stimulus-locked response or
  - phase resetting of ongoing activity? (Shah et al., Cer.Cortex (2004); Makeig et al., Science (2002))
Definitions

Let there be a signal $s(t) \in \mathbb{R}$

- decomposition of $s(t)$ into instantaneous
  - amplitude $A(t)$
  - phase $\phi(t)$

- instantaneous frequency $\nu(t)$ is related to the phase by $\phi(t) = \nu \cdot t$
  → phase definition possible by frequency analysis, e.g. by
    - Wavelet analysis
    - Fourier analysis (Gabor transformation)
    - Hilbert transformation
The analytical signal concept

\[ \tilde{s}(t) = s(t) + iH(t) \quad , \quad H(t) = \frac{1}{\pi} \text{PV} \int_{-\infty}^{\infty} \frac{s(\tau)}{t - \tau} d\tau \]

\[ = A(t)e^{i\phi(t)} \]

- but: instantaneous phase is physically relevant for narrow frequency bands only
- instantaneous power \( P(t) = |A(t)|^2 \)
- instantaneous phase \( \phi(t) = \arctan(H(t)/s(t)) \)
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Visuo-motor experiment

- 21 bipolar chronically implanted electrodes in awake behaving monkeys in multiple visual, parietal, sensoromotor and motor areas
- 4 visual stimulus events, 4 corresponding accomplished motor tasks, final reward (unknown to method)
- Local Field Potentials at 17 different spatial locations (unknown to method)
- Sample rate 1000Hz, ~3000-5000 time points
Problems and solutions in data analysis
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Problems and solutions in data analysis

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Instantaneous power

(Chaos and Complexity, accepted (2006))

Detection of synchronization in single brain signals
**Mutual phase synchronization**

- \( N \) measurement channels, \( N(N - 1)/2 \) phase pairs
  \[ \Phi_1(t) = \phi_1(t) - \phi_2(t), \]
  \[ \Phi_2(t) = \phi_1(t) - \phi_3(t), \ldots \]

- clustering of \( N(N - 1)/2 \)-dimensional signal

- clusters represent time windows, in which all phase differences \( \{ \Phi_j(t) \} \) show mutual behavior

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Detection of synchronization in single brain signals
Conventional global phase synchronization

circular variance computed in sliding window:

\[
R_n^2(t) = \frac{1}{T} \sum_{i=-T/2}^{T/2} \cos^2 \Phi_n(t + i\Delta T) + \sin^2 \Phi_n(t + i\Delta T)
\]

\[
R(t) = \frac{2}{N(N-1)} \sum_{n=1}^{N(N-1)/2} R_n
\]

\(n = 1, \ldots, N(N - 1)/2\): number of phase couples

Width of time window \(\Delta T\) is rather arbitrary.

\((\Delta T = 50)\)
Outlook

- study of the LFP in receptor cells/ELL in electric fish: detection of mutual synchronisation or mutual phase synchronization
- extension of method to partial synchronization
- meaning of the instantaneous power spectrum
- relation power and phase