# Delay Differential Analysis of Epilepsy iEEG Data

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DDA

# Delay Differential Analysis (DDA)



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DDA is done in the time domain, not in the spectral domain!

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 $\Rightarrow$  coefficients *a* and model error  $\rho$  as features to identify **dynamical** differences in data

# Advantages of DDA



- Preprocessing: normalizing to zero mean, unit variance
- Computationally fast
- Works for short time series
- Small feature space, no overfitting
- Noise insensitive

- 50 million people worldwide have epilepsy
- seizures: sudden breakdown of the neuronal activity of the brain ⇒ involuntary alteration in behavior, movement, sensation, or consciousness
- medication and therapy:
  - medication has considerable side effects
  - some patients have seizures despite maximal medical therapy
  - surgery

# Surgery

- 50 million people worldwide have epilepsy
  - $\bullet~>50$  % of Epilepsy patients: focal epilepsy
  - 30 % of these patients: seizures despite maximal medical therapy
- regional surgical resection: seizure reduction or even cure
- crucial importance: reliably localize the epileptic brain area(s)
  - intracranial EEG that contains seizure activity to determine the seizure onset area
  - seizures usually do not occur frequently ⇒ recordings must last a long time (from several days to several weeks) until sufficient seizures have occurred (typically between 3 and 5)

#### Seizures and Classical DDA



Coefficient  $a_1$  for 113 channels for patient 1. In the upper panel  $a_1$  for each channel is shown in a different color. The lower panel shows the values of  $a_1$  as color across all 113 channels (rows) to identify the onset channels. The onset channels marked by the neurologist are indicated by stars on the *y*-axis. The dotted line marks the seizure onset from the neurologist.

A chimera state is a spatiotemporal pattern of broken symmetry, where synchrony (coherent state) and asynchrony (incoherent state) coexist.

In [C. Lainscsek, N. Rungratsameetaweemana, S.S. Cash, and T.J. Sejnowski. Chaos, 29(12):121106, 2019] we report chimera states in electrocorticography (ECoG) recordings preceding, by several hours, each of seven seizures in one patient with epilepsy. Before the seizures, the onset channels are not synchronized, while the remaining channels are synchronized. During the seizures, this pattern of behavior reverses and the non-onset channels show more asynchronous behavior. At seizure offset, synchrony can be observed that might facilitate termination.

This is, to the best of our knowledge, the first direct evidence of chimera states in the human epileptic brain.



DDA feature  $a_1$  (left) and phases of the DDA feature  $a_1$  (right) corresponding to each of the 77 recording channels for patient 2 over time. The top panel shows over 100 hours of recording. The bottom panel zooms in on the hour 100 to hour 120 of recording, during which all seven seizures occurred. The recording channels are sorted such that the onset channels, as determined by the neurologist, are shown here as channel number 1–32 and the non-onset channels are shown here as channel number 33–77. The onset of each of the seven seizures is indicated by an arrow. Missing data are marked in grey.



Phases for two time points, 10 minutes before and 10 minutes after the fourth seizure: The onset channels (the first 32 channels) show desynchronization before the seizure onset with coexisting synchronized non-onset channels. After the seizure all channels are well synchronized. The colors of the dots in the circular phase plots are identical to those in the phase by channel number plots.



Seizure 4: Phases (upper panel) for 77 channels and Kuramoto order parameter:

$$\mathcal{O}(t) = \frac{1}{N} \sum_{k=1}^{N} e^{i\phi_k(t)}$$

(lower panel) from 1 minute before seizure onset (dashed line) to 2 minutes after seizure onset.

#### All 7 seizures:





DDA order parameter. A: 100 hours of data from 77 channels; B: zoomed in version of 20 hours around the seven seizures: C and D: DDA order values for the individual channels.

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# Cross-Dynamical Delay Differential Analysis (CD-DDA)



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# Cross-Dynamical DDA (CD-DDA)



$$\mathcal{C}_{xy} = \mid \rho_{xy} - \rho_x \mid, \ \mathcal{C}_{yx} = \mid \rho_{yx} - \rho_y \mid$$

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### Information flow using CD-DDA



In the upper panels of (a) and (b)  $C_{vu}$  for all channels u to one channel v (onset channel in (a) and non onset channel in (b)) is shown and in the lower panels  $C_{\mu\nu}$  for one channel v (onset channel in (a) and non onset channel in (b)) to all other channels u is shown. The onset channels marked by the neurologist are indicated by stars on the y-axis. (d): The left panel shows the channel locations and the right panel shows a grid of these locations. The boxes in gray scale are the  $C_{\mu\nu}$  values or information sent by the onset channel to all other channels at the time of the highest peak in the upper panels in (a), at around 10 seconds after the seizure onset marked by the neurologist. The circles indicate the onset channels determined by the neurologist. The darker magenta boxes are background and the lighter magenta boxes indicate bad channels.

Image: A mathematical states and a mathem

#### Information flow for all seizures for patient 1















#### Information flow using CD-DDA



Time line of the CD-DDA feature  $C_{uv}$  and the classical DDA feature  $a_1$ . The window length for each box is a quarter of a second with a window shift of half that length. The features  $C_{uv}$  and  $a_1$  are mapped onto the same grid and color axis as in the figure before with a white background.

Image: Image:

# Thank you!

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The Chaos Tower

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