UC San Diego
Jacobs School of Engineering

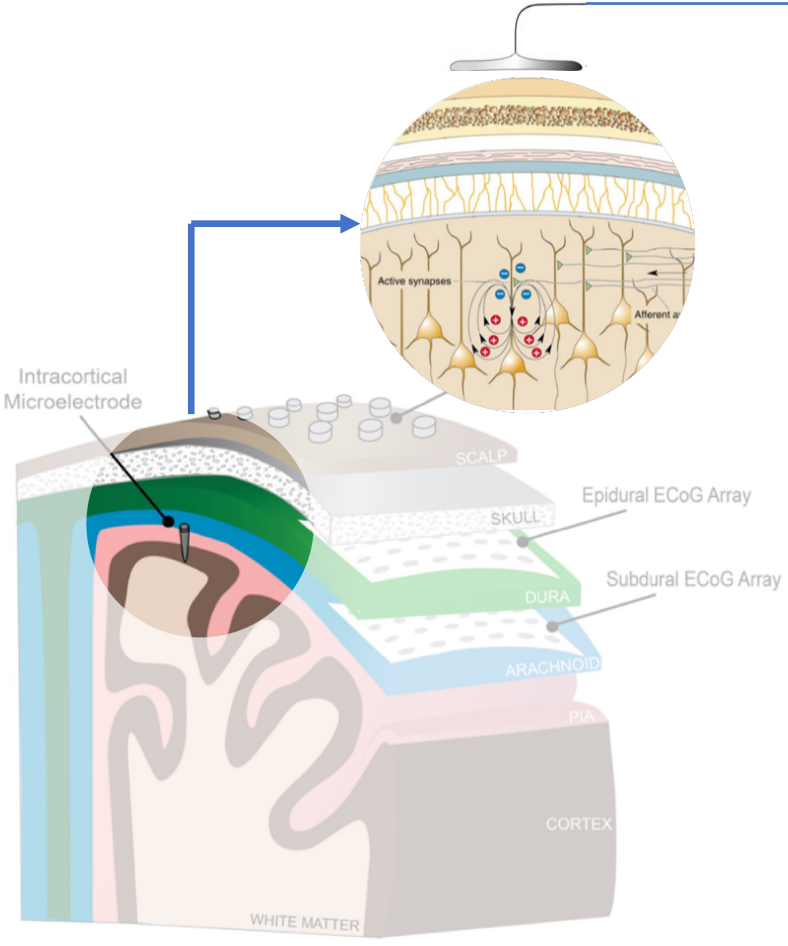
Swartz Center for Computational Neuroscience

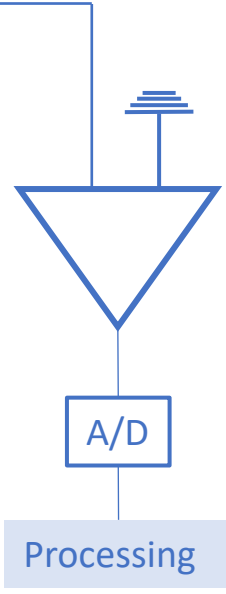
BRAIN PRODUCTS
Solutions for neurophysiological research

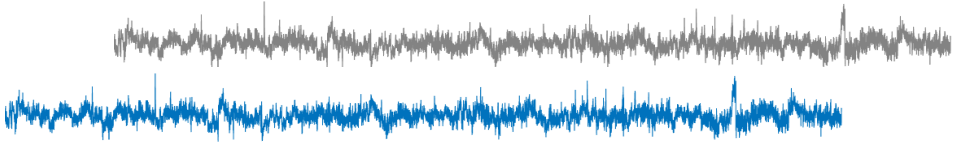
PACTools

Computing Phase Amplitude Coupling in EEGLAB

Ramon Martinez-Cancino



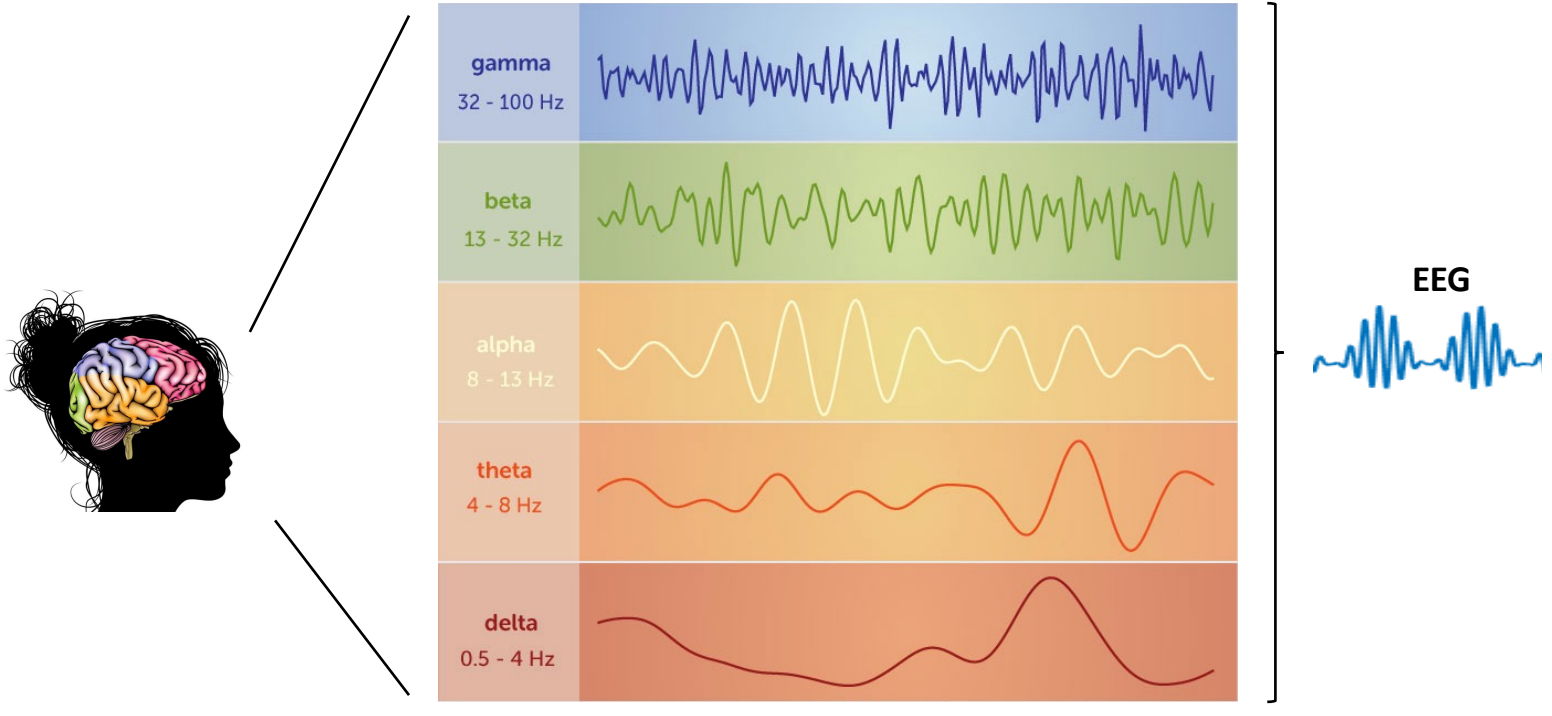




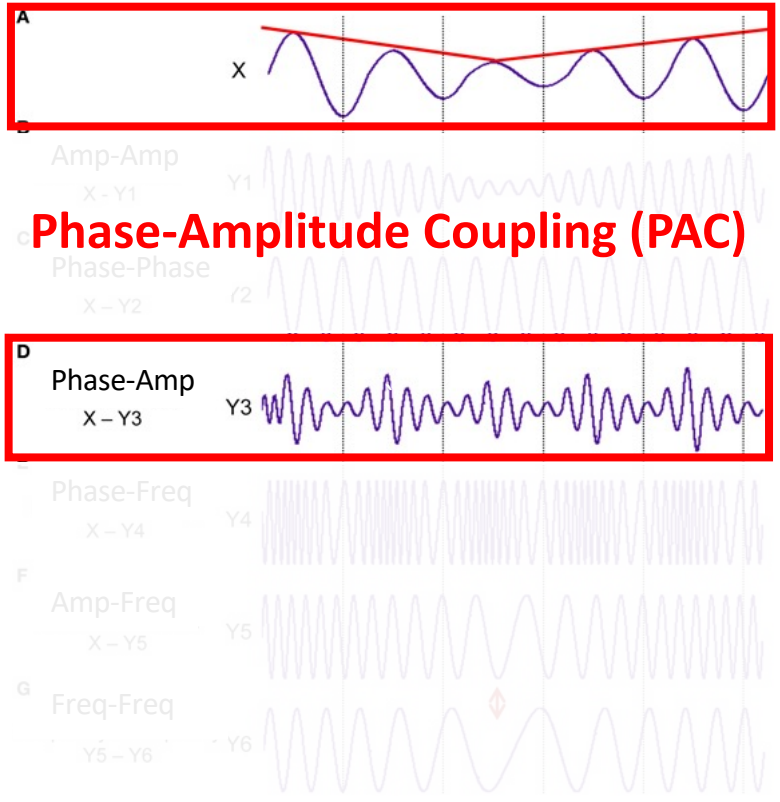
CROSS-FREQUENCY COUPLING

Jorfi et al, 2014

Brain oscillations and CFC



Cross-Frequency Coupling



Phase-Amplitude Coupling (PAC)

Epilepsy

Parkinson's disease

Alzheimer's disease

Schizophrenia

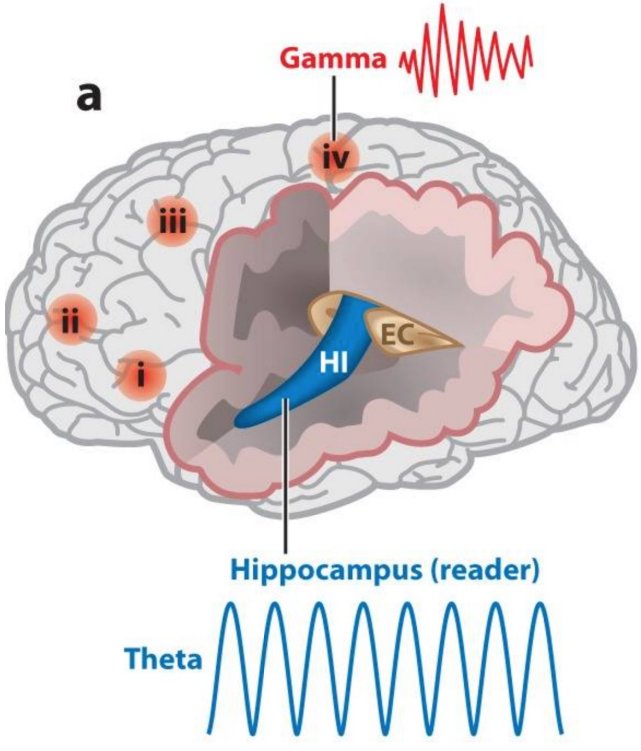
Obsessive-compulsive disorder

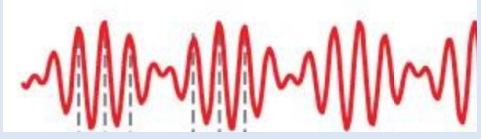
Mild cognitive impairment

(Mormann et al., 2005; Cohen, 2008; Osipova et al., 2008; Tort et al., 2008, 2009, 2010; Cohen et al., 2009a,b; Colgin et al., 2009; Axmacher et al., 2010a,b; Voytek et al., 2010)

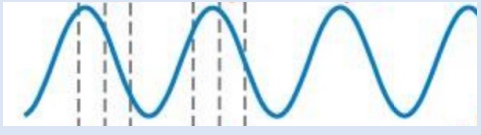
Jirsa and Muller, 2013 Front. Comput. Neurosci.

PAC suggest an architectural hierarchy





Small functional areas



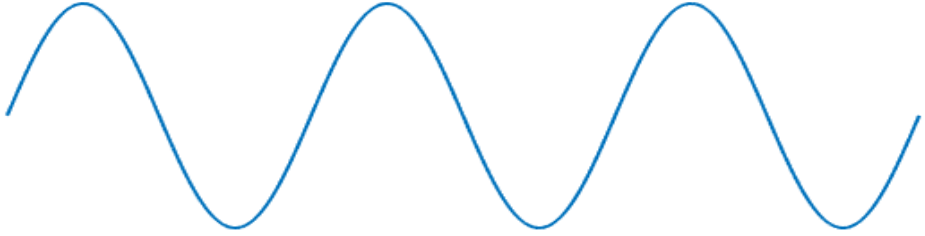
Large areas
or
coupled networks

Buzsáki, György, and Xiao-Jing Wang. "Mechanisms of gamma oscillations." Annual review of neuroscience 35 (2012): 203-225.

PAC and Amplitude Modulation

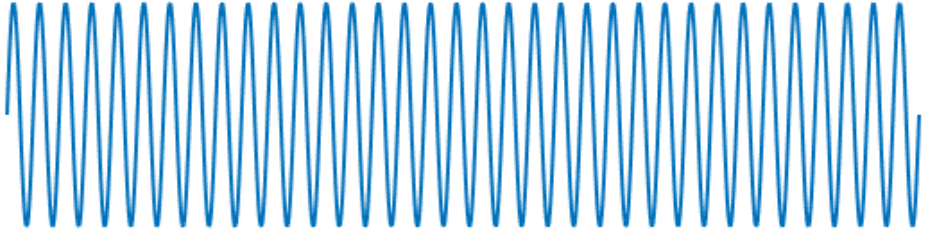
Modulator

$$v_{\text{mod}} = V_{\text{mod}} \sin\left(2\pi f_{\text{mod}} t\right)$$



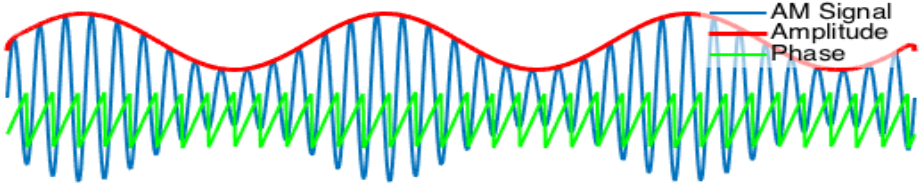
Carrier

$$v_{carr} = V_{carr} \sin\left(2\pi f_{carr} t\right)$$



AM Signal

$$v_{AM} = V_{carr} \sin\left(2\pi f_{carr} t\right) + \left[V_{\text{mod}} \sin\left(2\pi f_{\text{mod}} t\right)\right] \sin\left(2\pi f_{carr} t\right)$$



Instantaneous Phase and Amplitude

$$S_t = s_{m_t} e^{i\phi_t}$$

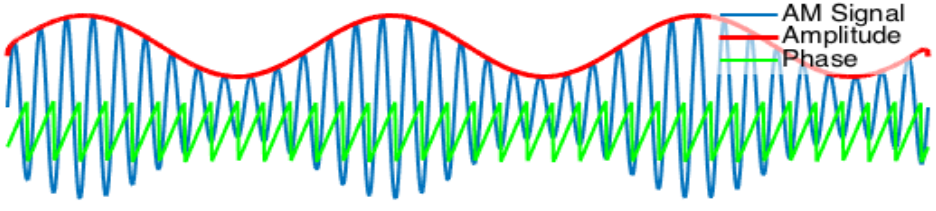
By means of the **Hilbert transform** a signal can be expressed as its **analytic signal**

$$S_{m_t} = |S_t|$$

Instantaneous amplitude (or the envelope)

$$\phi_t = arg[S_t]$$

Instantaneous phase.



$abs\left(hilbert(S_t)\right)$

$angle\left(hilbert(S_t)\right)$

Computing PAC

Extracting components

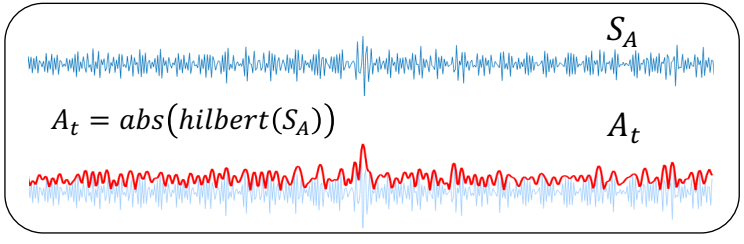
Assessing correlation

Statistical evaluation

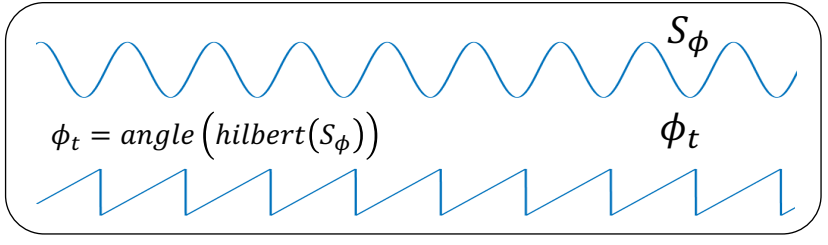
Electrophysiological signal

Band-pass Filter

High frequency band f_{Amp} (e.g: 30-50Hz)

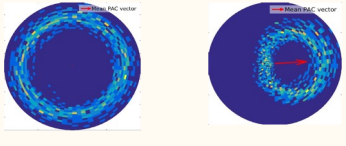


Low frequency band f_{phase} (e.g: 5-12Hz)



Mean Vector Length *(Canolty et al. 2006)*

$z_t = A_t e^{i\phi_t}$



No Coupling Coupling

Kullback-Leibler MI *(Tort et al. 2010)*

No Coupling Coupling

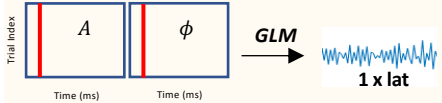
GLM Measure *(Penny et al. 2008)*

$$A_t = X\beta + e$$

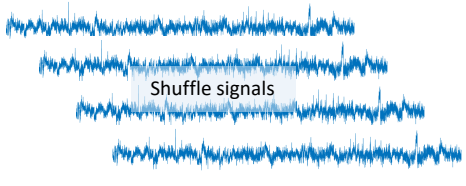
$$X = \begin{vmatrix} cos\phi_1 & sin\phi_1 & 1 \\ \vdots & \vdots & \vdots \\ cos\phi_N & cos\phi_N & 1 \end{vmatrix}$$

Explained variance as an index of PAC

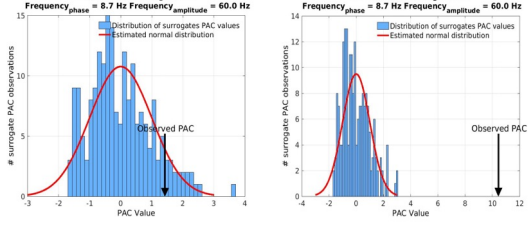
ERPAC *(Voytek et al. 2013)*



Time resolved '*average*' PAC by applying ***GLM Measure*** for each latency in event related data

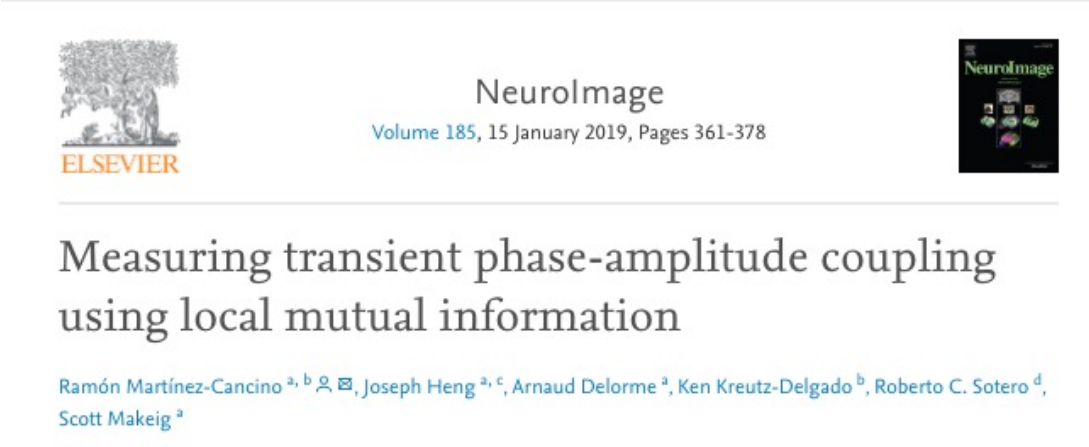


Compute PAC



MIPAC: Mutual Information Phase-Amplitude Coupling

Goal: Develop and validate an information-theory based approach to characterize PAC dynamics in electrophysiological signals from the brain



ELSEVIER

NeuroImage

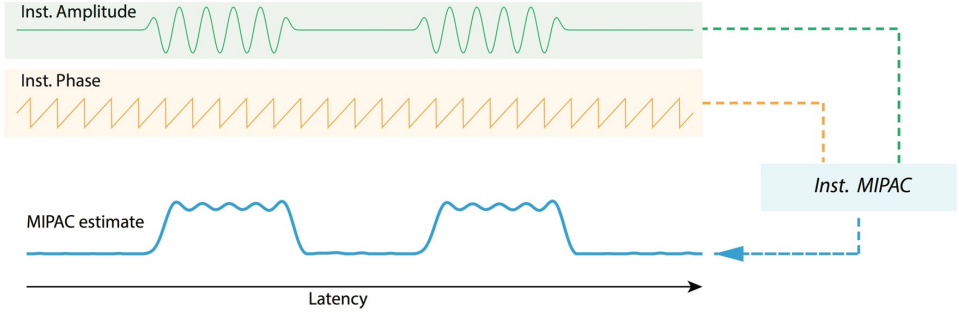
Volume 185, 15 January 2019, Pages 361-378

Measuring transient phase-amplitude coupling using local mutual information

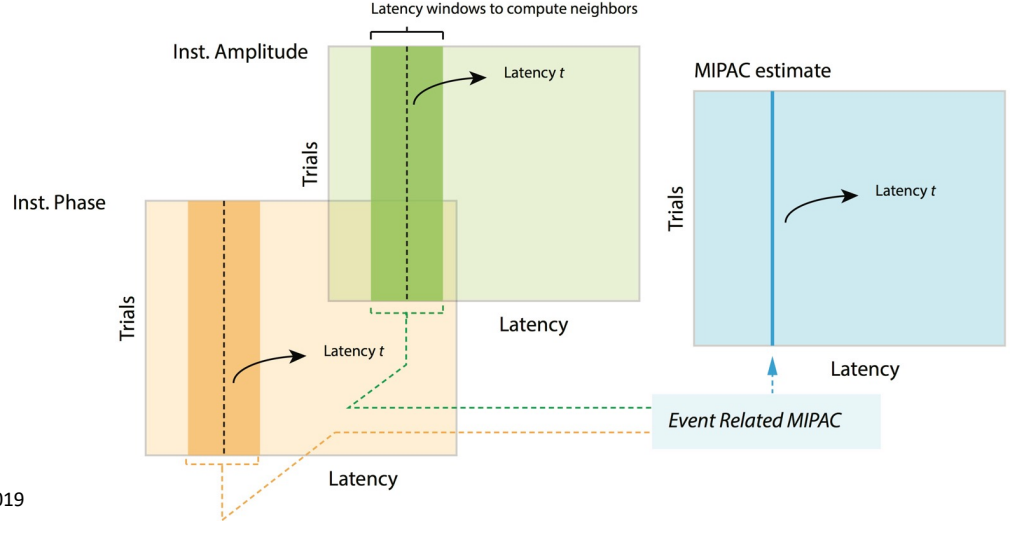
Ramón Martínez-Cancino [a, b], Joseph Heng [a, c], Arnaud Delorme [a], Ken Kreutz-Delgado [b], Roberto C. Sotero [d], Scott Makeig [a]

Inst. MIPAC and Event-related MIPAC

MIPAC

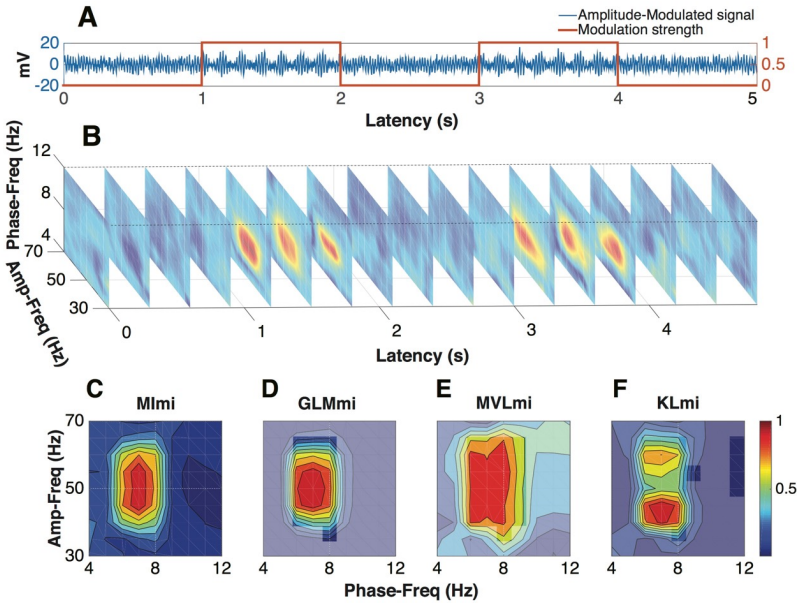


Event-related MIPAC

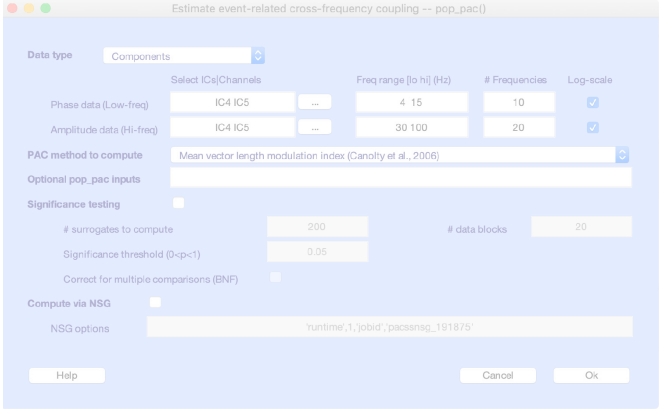


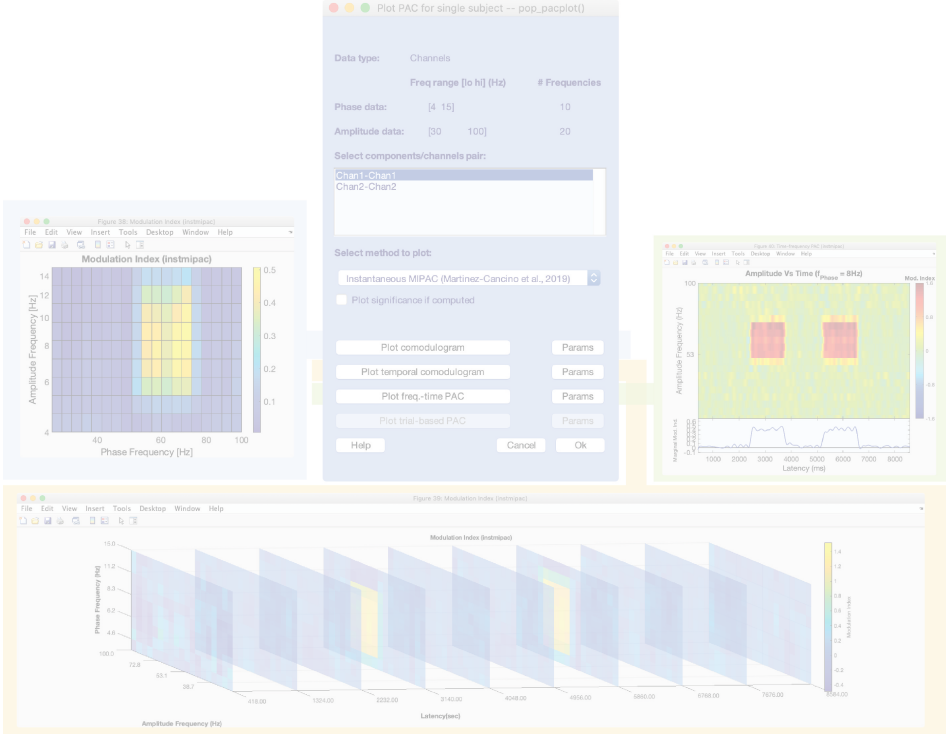
Martinez-Cancino et al, **Neuroimage** Volume 185, 2019

Simulations



PACTools: EEGLAB plug-in to compute phase-amplitude coupling






```
>> EEG.etc.eegpac(1)
    struct with fields:
    dataindx: [1 1]
    datatype: 1
    labels: {'Chan1-Chan2’}
    params: [1×1 struct]
    cache: [1×1 struct]
    glm:[1x1 struct]
    instmipac: [1×1 struct]
    mvlmi: [1×1 struct]
```

PACTools features

- Plug-in to EEGLAB for computing PAC
- Supports both ICs and channel data
- Running and written on MATLAB
- Command line and GUI access
- Parallelized code
- Built-in access to HPC resources

https://github.com/sccn/PACTools

(In next Section)

Methods implemented

Continuous data

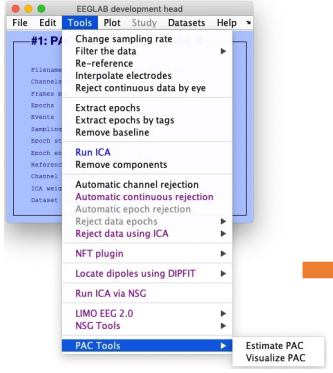
Method	Reference
Mean Vector Length Modulation Index	Canolty et al., 2006
Kullback-Leibler Modulation Index	Tort et al., 2010
General Linear Model Modulation Index	Penny et al., 2008
Phase Locking Value	Lachaux et al., 1999
Instantaneous Mutual Information PAC	Martinez-Cancino et al., 2019

Event-related data (Epoched data)

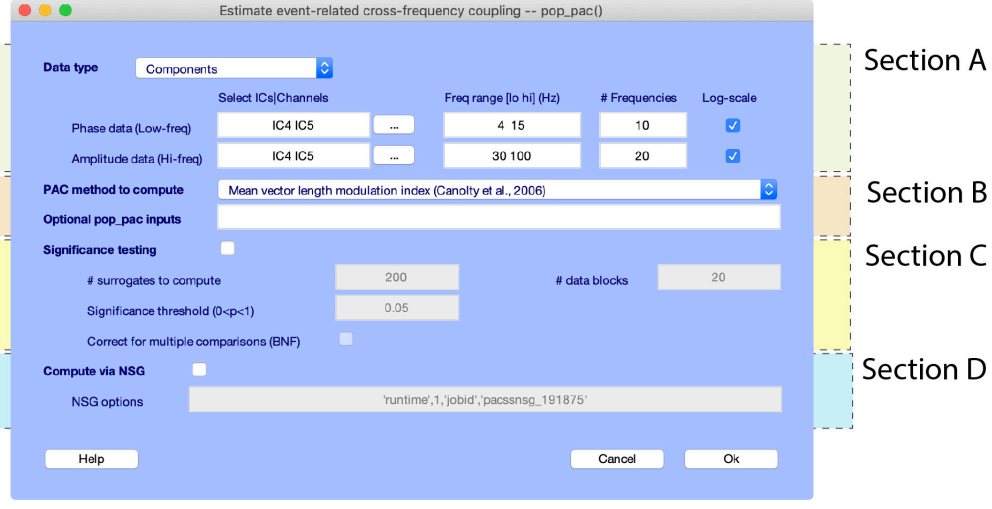
Method	Reference
Mean Vector Length Modulation Index	Canolty et al., 2006
Kullback-Leibler Modulation Index	Tort et al., 2010
General Linear Model Modulation Index	Voytek et al., 2013
Phase Locking Value	Lachaux et al., 1999
Event-Related Mutual Information PAC	Martinez-Cancino et al., 2019

PACTools graphic user interface

https://github.com/sccn/PACTools



Estimate PAC



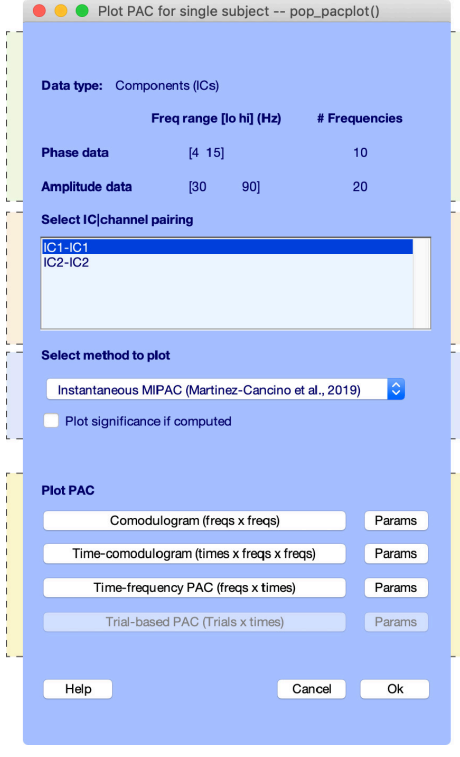
Section A

Section B

Section C

Section D

Vizualize PAC



Section A

Section B

Section C

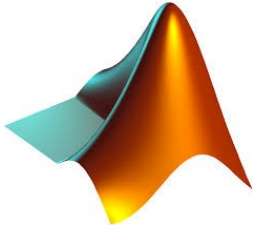
Section D

PACTools command-line tools

https://github.com/sccn/PACTools

Estimate PAC

```
EEG = pop_pac(EEG,'Channels',[4 15],[30
90],[1],[1],'method','instmipac','nfreqs1',10,'n
freqs2',20);
```



EEG structure

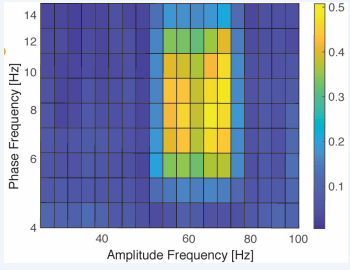
```
>> EEG.etc.eegpac(1)

  struct with fields:

     dataindx: [1 1]
     datatype: 1
       params: [1×1 struct]
    instmipac: [1×1 struct]
         klmi: [1×1 struct]
```

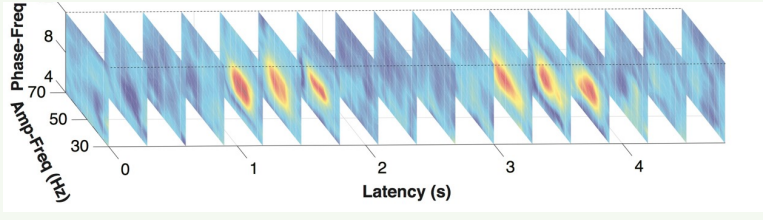
Vizualize PAC

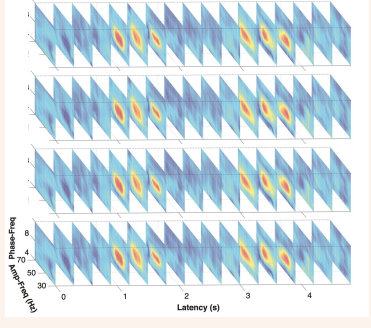
```
EEG = pop_plotpac(EEG,'method',klmi');
```

Dimension of PAC outputs

EEG data format	PAC Method	PAC result dimensions
Continuous	MVL-MI, KL-MI, PLV, GLM-MI	Single value
	instMIPAC	(1,# latencies)
Epoched	MVL-MI, KL-MI, PLV, GLM-MI	
	erMIPAC	(1,# latencies, # trials)







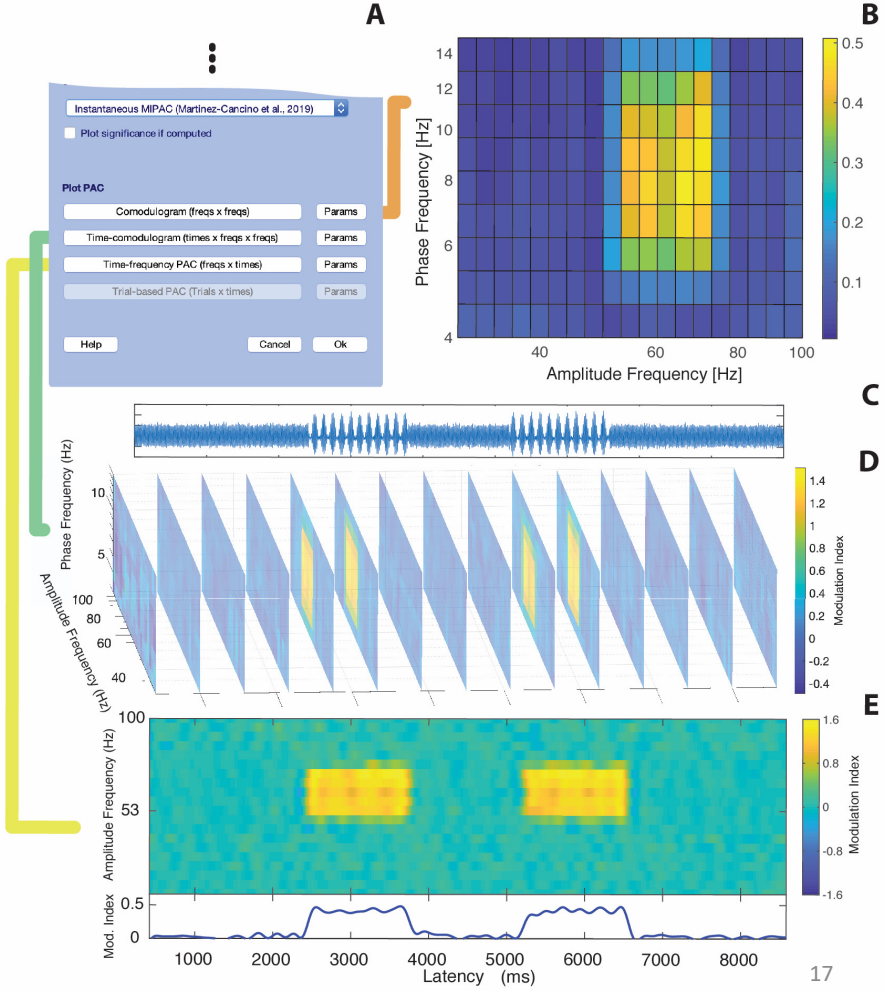
Mean Vector Length MI (**MVL-MI**) (*Canolty et al. 2006)*
Kullback-Leibler MI (**KL-MI**) (*Tort et al, 2010*)
Phase-Locking Value (**PLV**) *(Lachaux et al, 1999)*
General Linear Model MI (**GLM-MI**) *(Penny et al. 2008)*
Mutual Information MI (**MIPAC**) *(Martinez-Cancino, 2019)*

PACTools visualizations

Main type of plots

1. Comodulogram (freqs x time)
2. Time-comodulogram (times x freqs x freqs)
3. Time frequency PAC (freqs x times)
4. Trial-based PAC (trials x times)

PACTools have provisions to add more plot types under these groups



Storing PACTools results

```
>> EEG.etc.eegpac(1)
    struct with fields:
    dataindx: [1 1]
    datatype: 1
    labels: {'Chan1-Chan2’}
    params: [1×1 struct]
    cache: [1×1 struct]
    glm:[1x1 struct]
    instmipac: [1×1 struct]
    mvlmi: [1×1 struct]
```

Data index in array (e.g., channels)

Channels or ICs

Labels of data streams

Parameters of computation

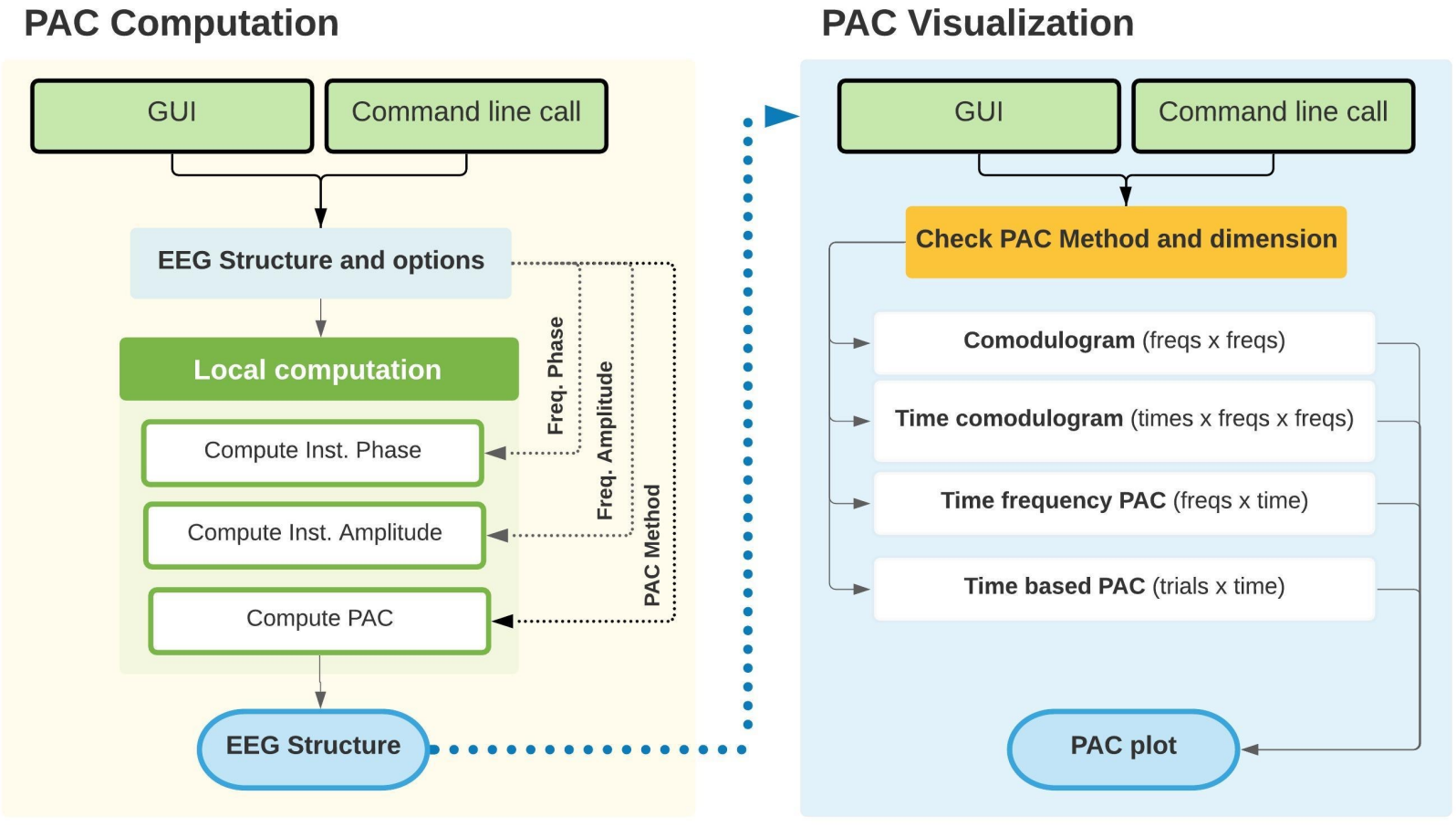
Results for specific methods

```
>> EEG.etc.eegpac(1).params
    struct with fields:
    freqs_phase: [4:2:15]
    freqs_amp: [30:5:90]
    signif: [1×1 struct]
    srate: 500
```

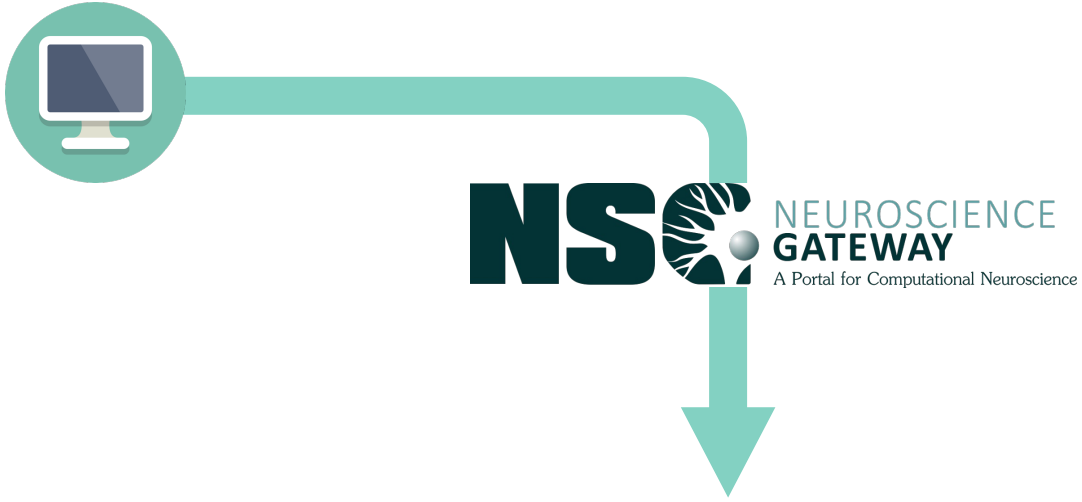
Phase frequency

Amplitude frequency

PACTools workflow



Neuroscience Gateway



NSG NEUROSCIENCE GATEWAY
A Portal for Computational Neuroscience

NSF

XSEDE Extreme Science and Engineering Discovery Environment

UCSD Comet

2.76 petaflops
1944 nodes
24 cores

UT Austin Stampede 2

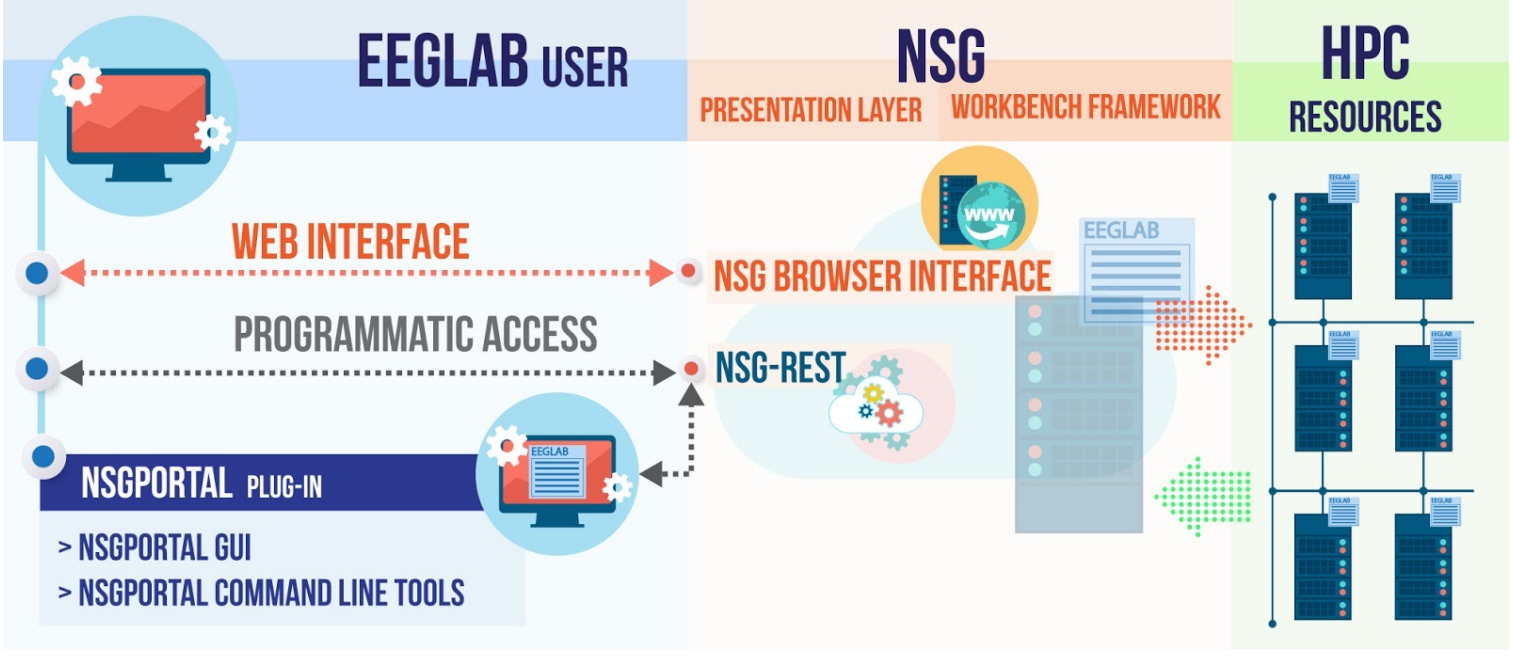
18 petaflops
4200 nodes/68 cores
1736 nodes/48 cores

Jetstream U. of Indiana

0.5 petaflops
320 nodes/24 cores X 2

Sivagnanam, S., Majumdar, A., Yoshimoto, K., Astakhov, V., Bandrowski, A., Martone, M.E. and Carnevale, N.T., 2013, June. Introducing the Neuroscience Gateway. In IWSG.

The Open EEGLAB Portal



Martínez-Cancino, R., Delorme, A., Truong, D., Artoni, F., Kreutz-Delgado, K., Sivagnanam, S., Yoshimoto, K., Majumdar, A. and Makeig, S., 2020. The Open EEGLAB Portal Interface: High-Performance Computing with EEGLAB. NeuroImage, p.116778.

EEGLAB plug-in *nsgportal*

https://github.com/sccn/nsgportal

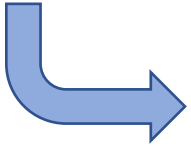
Command-line tools

- **Create** and run NSG job (*pop_nsg.m* option 'run')
- **Test job** on local computer (*pop_nsg.m* option 'test')
- **Retrieve results** (*pop_nsg.m* option 'output')
- **Delete job** (*pop_nsg.m* option 'delete')
- **Recursive check** of job status (*nsg_recurse.m*)

Command window

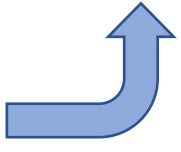
```
[currentjob, alljobs] = pop_nsg('run',path2zip,'filename',
                                'run_ica_nsg.m');
```

RESTFUL Service

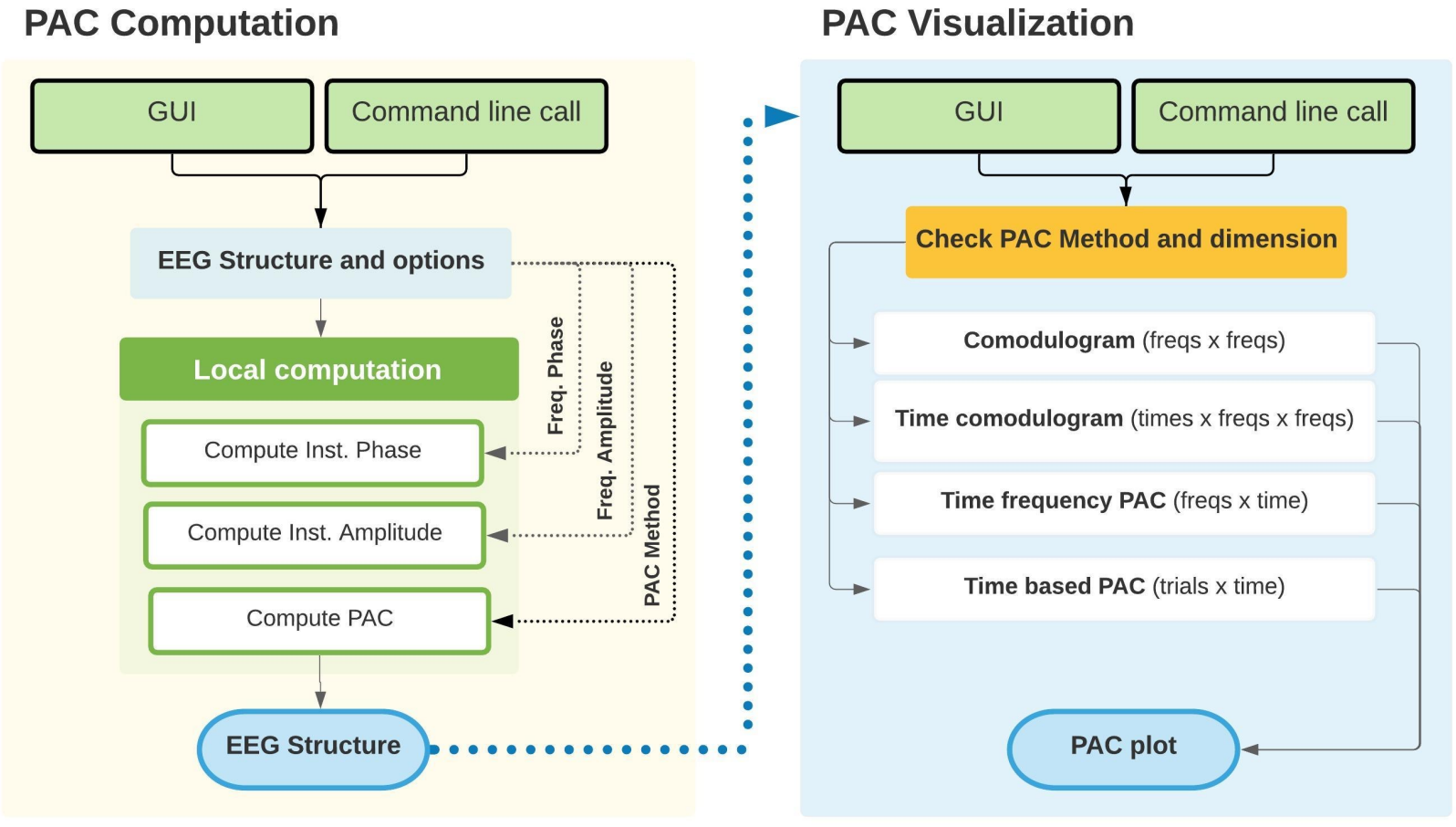


Command line terminal

```
curl -s -u your_username:your_password \
        -H cipres-appkey:$KEY \
         $URL/job/your_username \
        -F tool=EEGLAB_TG \
        -F input.infile_=@"/data/TestingEEGLABNSG.zip" \
        -F vparam.filename_=run_ica_nsg.m
        -F metadata.clientJobId=TestingEEGLABNSG \
        -F vparam.outputfilename_="nsgresults_TestingEEGLABNSG" \
        -F vparam.number_nodes_=1 \
```



PACTools workflow with HPC



Limitations and future work

- Single subject computation
- PAC Computation in STUDY (80% Done)

PACTools in a nutshell

- Toolbox for computing PAC in EEGLAB with parallelized code and access to HPC
- Open-source code
- Extensive documentation allow further inclusion of new methods

THANKS!!!!

Ken Kreutz-Delgado

UC San Diego
Jacobs School of Engineering

Arnaud Delorme

Scott Makeig

Swartz Center for Computational Neuroscience

BRAIN PRODUCTS
Solutions for neurophysiological research