Time-frequency decomposition

Theory and Practice

2022 EEGLAB Workshop San Diego

N170

Pernet_pdfs	11/18/2022 10:27 AM	File folder	
EEGLAB_STERN_STUDY	11/18/2022 10:52 AM	Compressed (zipped)...	1,881,192 KB
faces_3.locs	11/18/2022 10:52 AM	LOCS File	1 KB
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FACES_README	11/18/2022 10:52 AM	Text Document	1 KB
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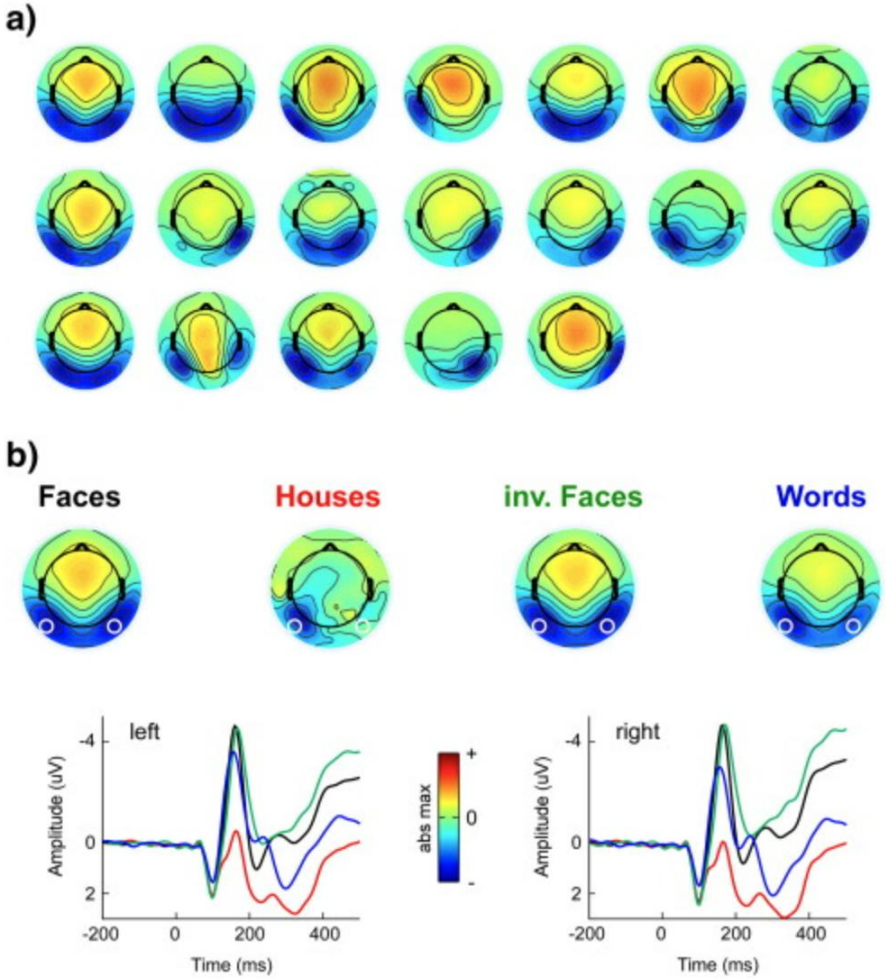
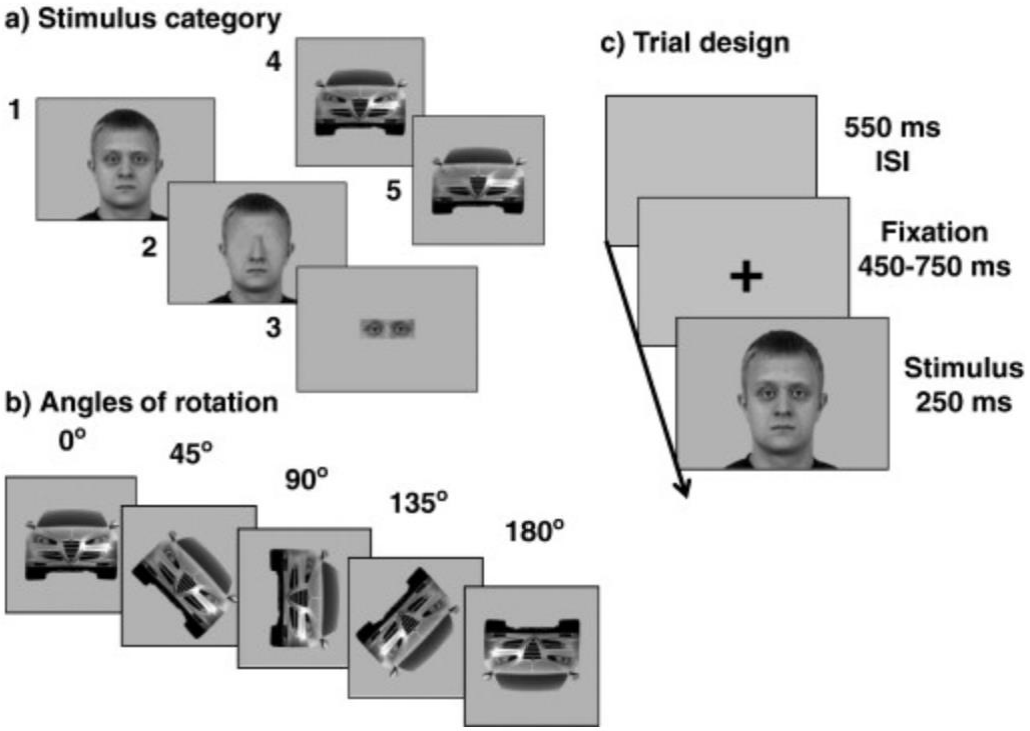
N170



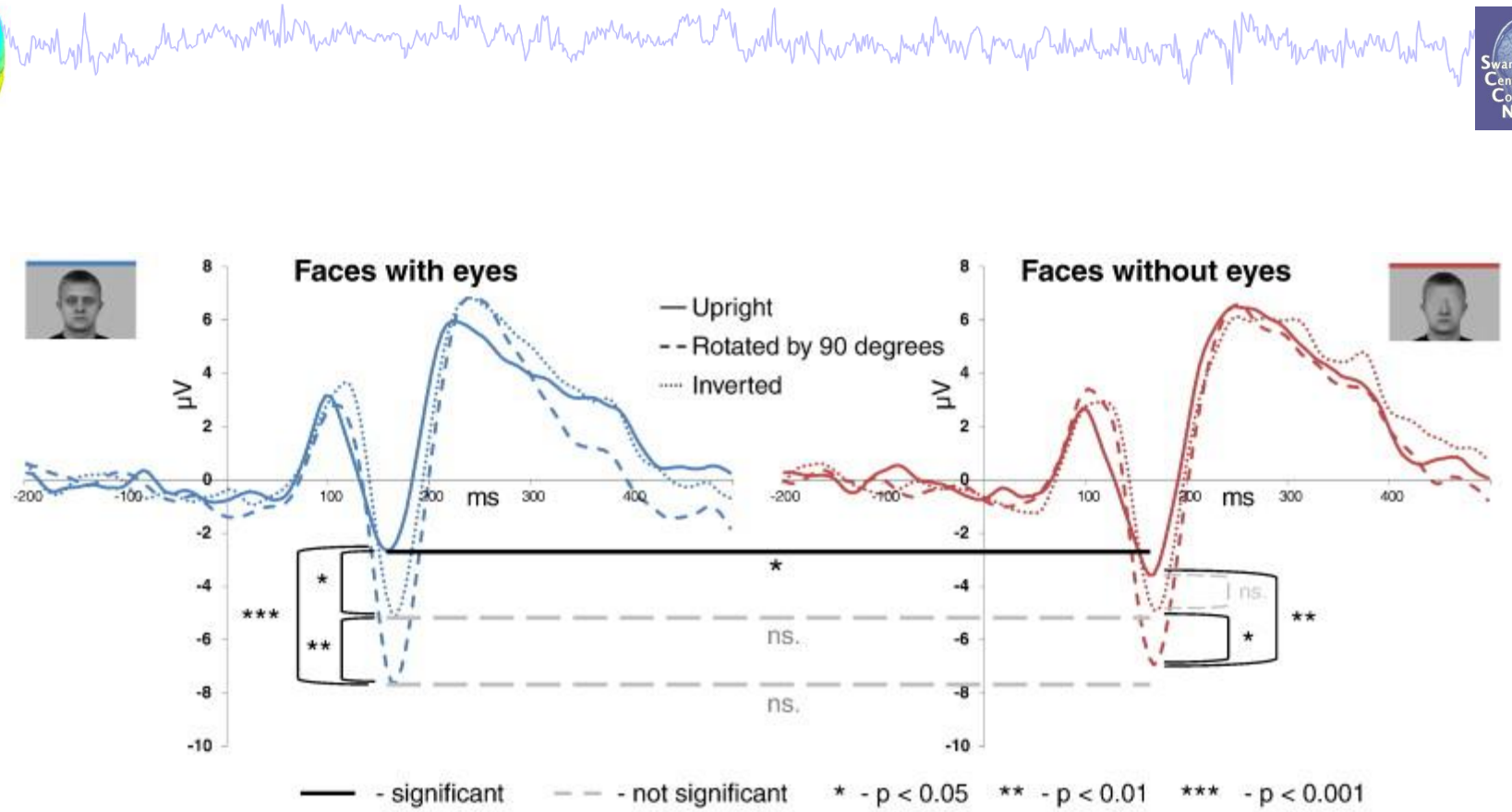
De Vos, M., Thorne, J. D., Yovel, G., & Debener, S. (2012). Let's face it, from trial to trial: comparing procedures for N170 single-trial estimation. *Neuroimage*, *63*(3), 1196-1202.

N170



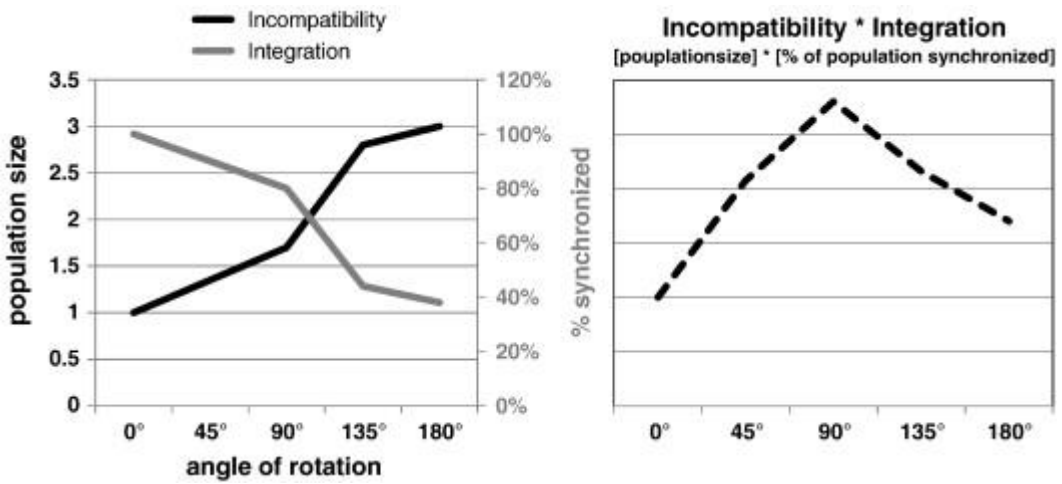
Magnuski, M., & Gola, M. (2013). It's not only in the eyes: Nonlinear relationship between face orientation and N170 amplitude irrespective of eye presence. *International Journal of Psychophysiology*, *89*(3), 358-365.

N170



Magnuski, M., & Gola, M. (2013). It's not only in the eyes: Nonlinear relationship between face orientation and N170 amplitude irrespective of eye presence. *International Journal of Psychophysiology*, *89*(3), 358-365.

N170

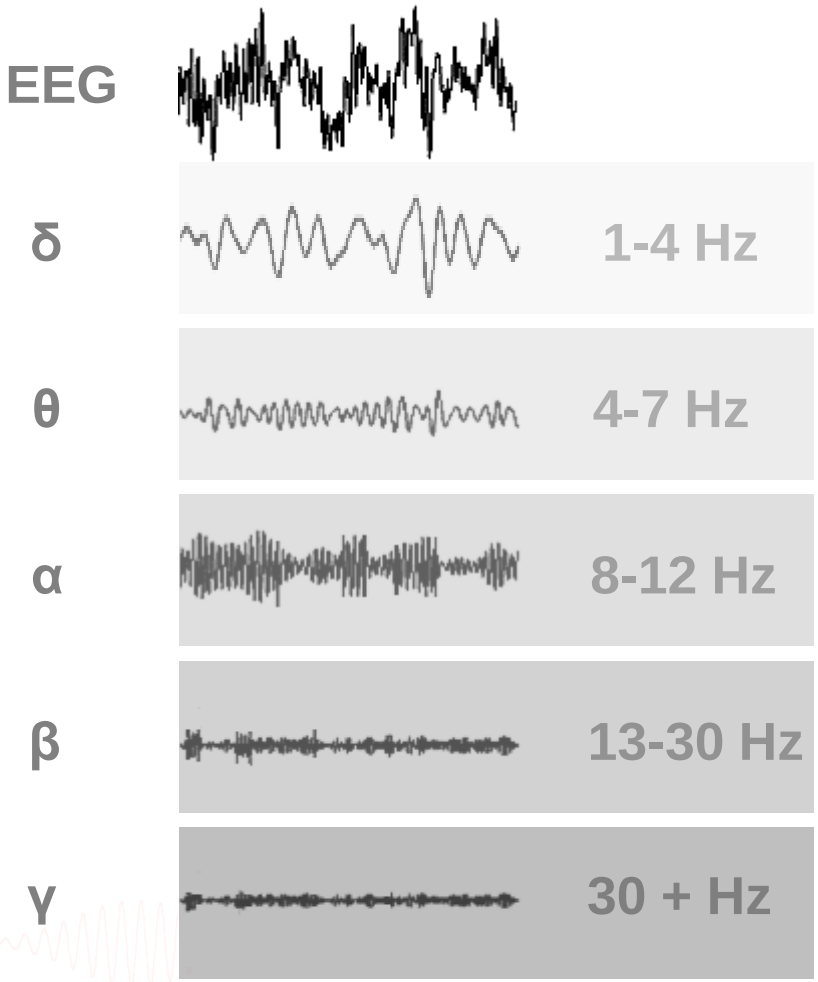


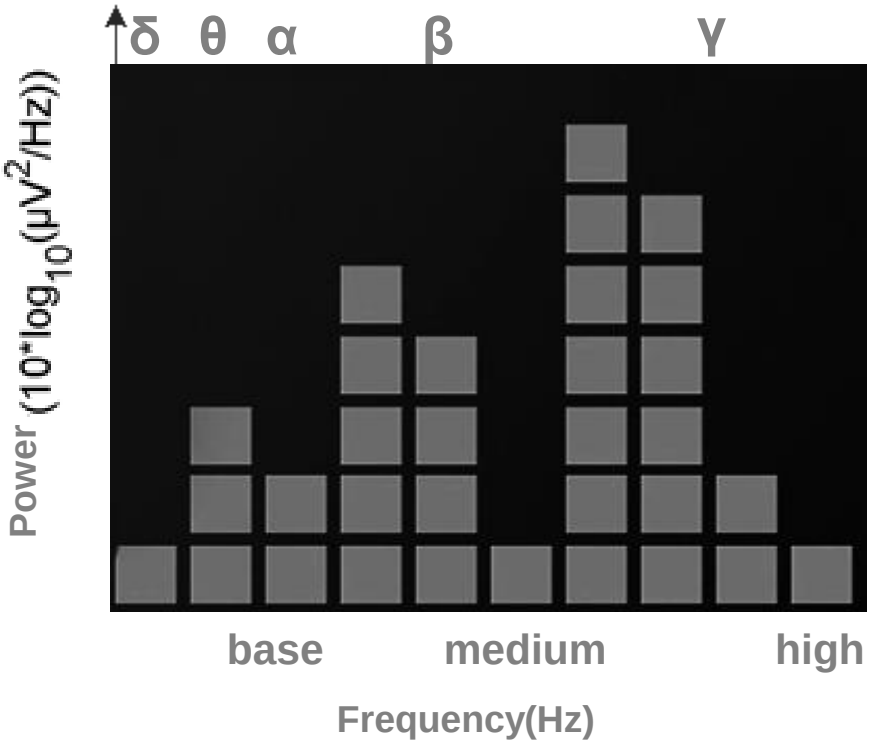
Magnuski, M., & Gola, M. (2013). It's not only in the eyes: Nonlinear relationship between face orientation and N170 amplitude irrespective of eye presence. *International Journal of Psychophysiology*, *89*(3), 358-365.

- Signals – EEG
- Goals
  - Describe dynamic characteristics of brain activity
- Approaches
  - Time domain
  - Frequency domain
  - Time/Frequency

Introduction: Spectral analysis of the EEG signal

EEG Signal





Different meanings traditionally given to different frequency bands

Beta 15-30 Hz

Awake, normal alert consciousness

Alpha 9-14 Hz

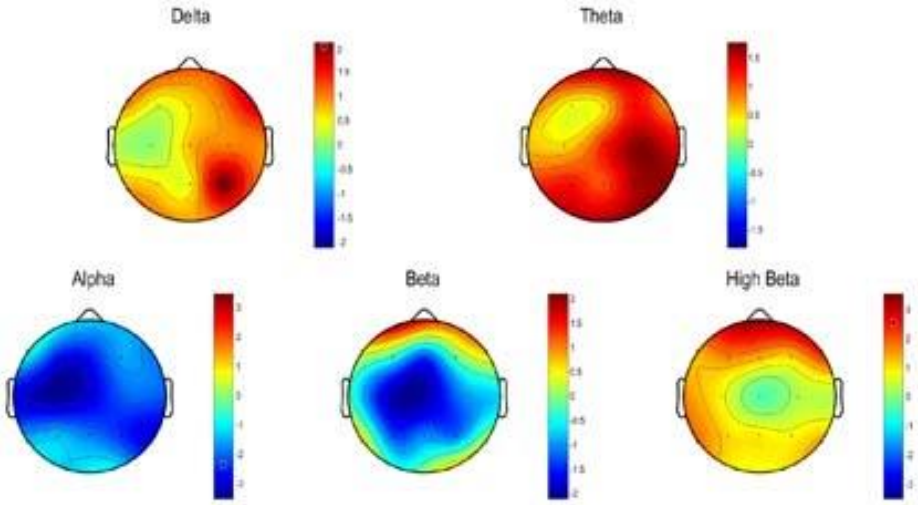
Relaxed, calm, meditation, creative visualisation

Theta 4-8 Hz

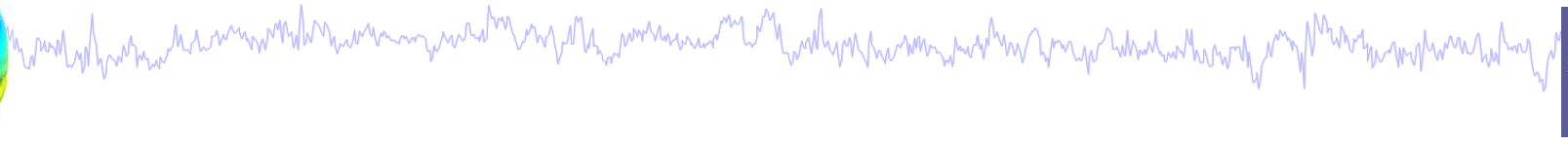
Deep relaxation and meditation, problem solving

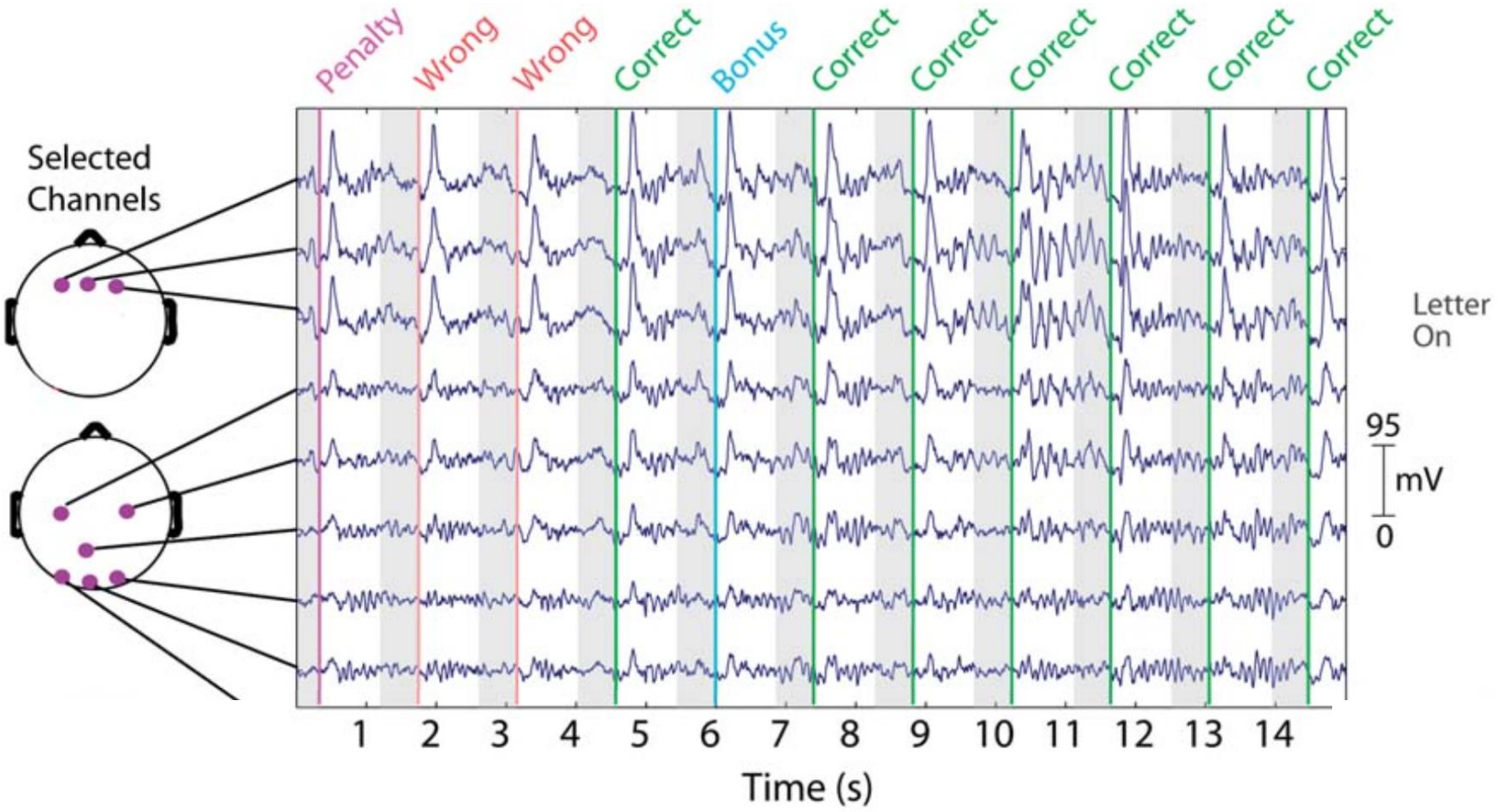
Delta 1-3 Hz

Deep, dreamless sleep

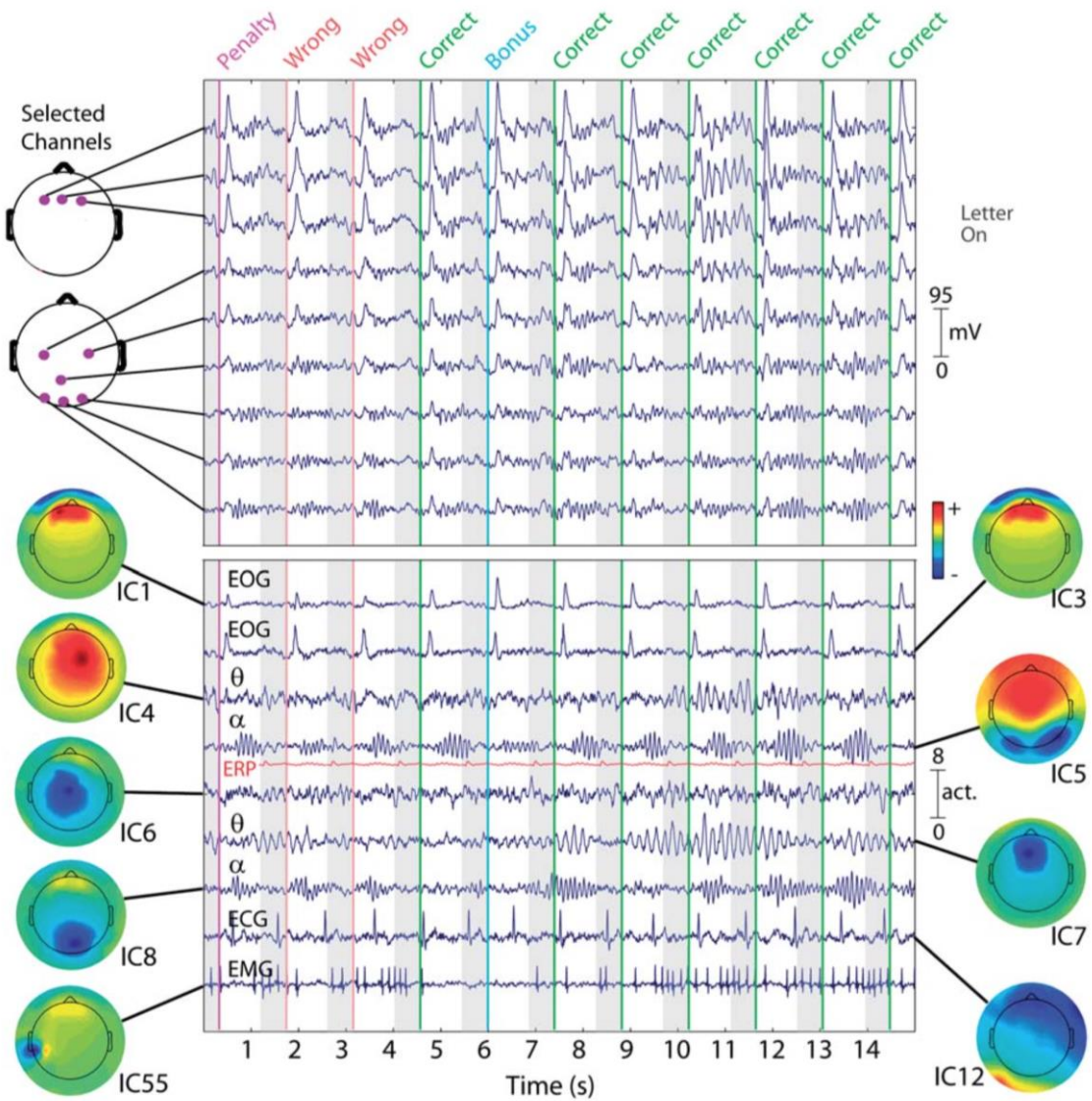


Time varying frequency content



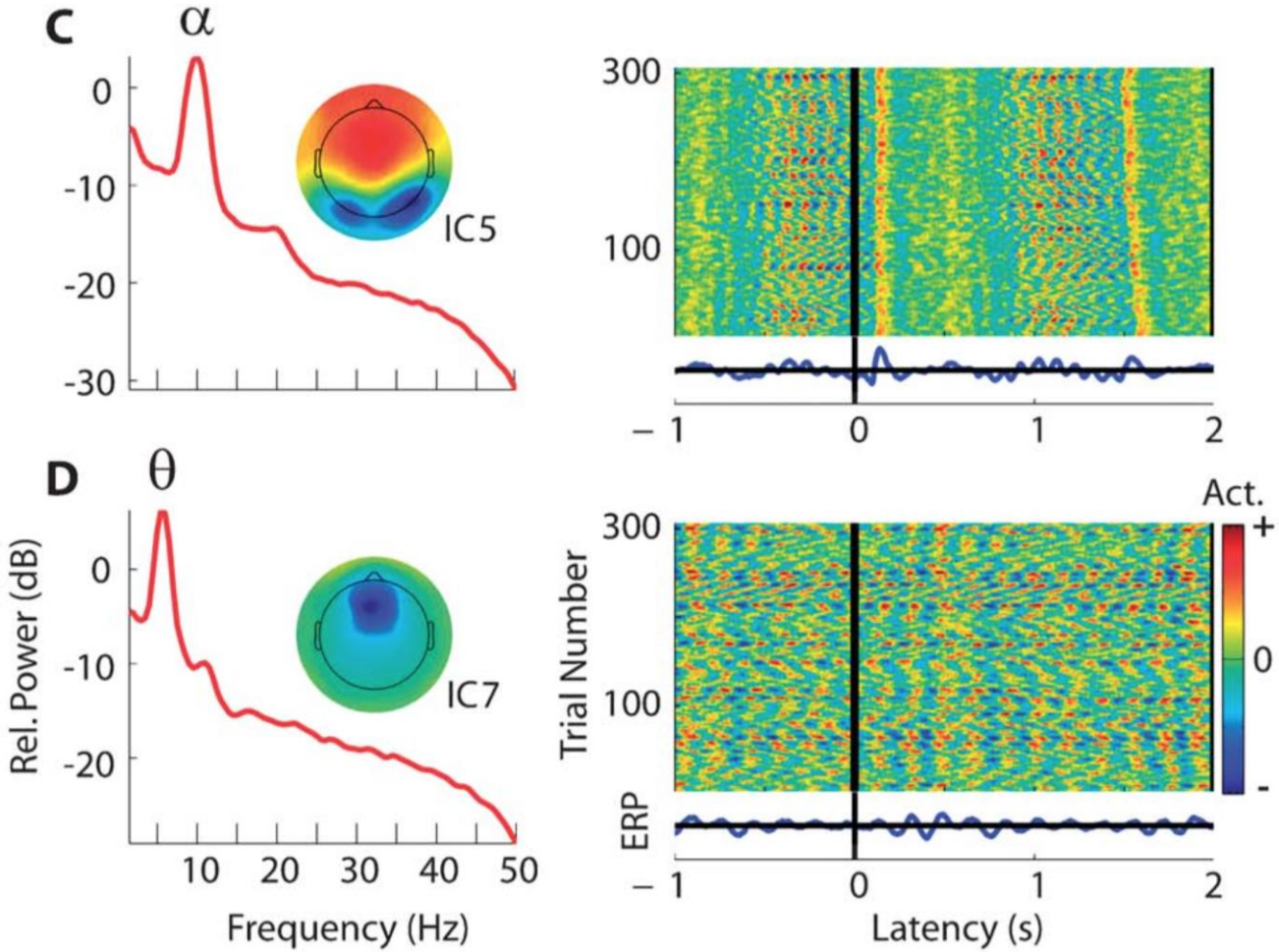


Time-varying frequency content

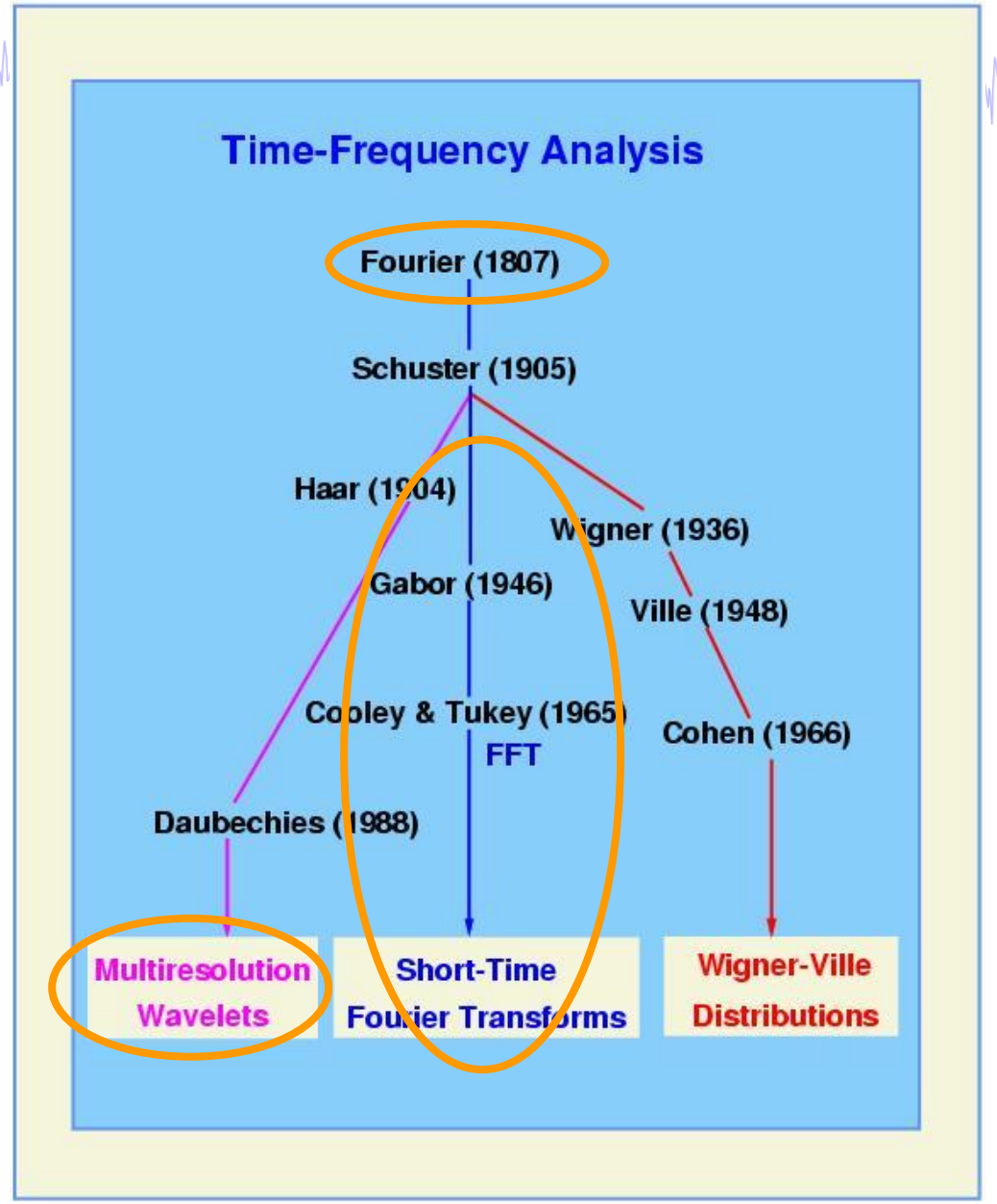


Onton & Makeig, 2006

Power Spectrum does not describe temporal variation



Onton & Makeig, 2006



S. Makeig, 2005

Plan

- **Part 1: Frequency Analysis**
  - Power Spectrum
    - Approaches
      - FFT
      - Welch's Method
    - Windowing

- **Part 2: Time-Frequency Analysis**
  - Short Time Fourier Transform
  - Wavelet Transform
  - ERSP

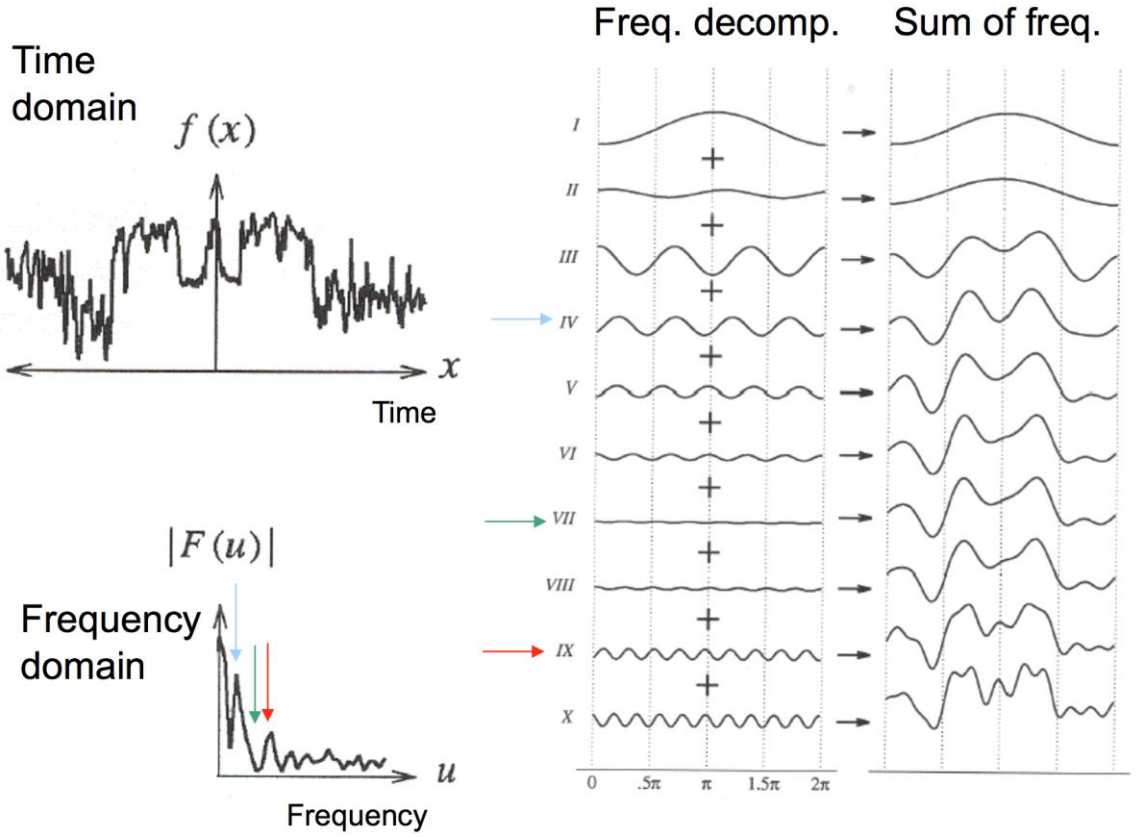
- **Part 3: Coherence Analysis**
  - Inter-Trial Coherence
  - Event-Related Coherence

- **Part 4: Other Applications**

Part 1: Frequency Analysis

- Goal: What frequencies are present in signal?
- What is power at each frequency?
- Principle: Fourier Analysis

Fourier Analysis

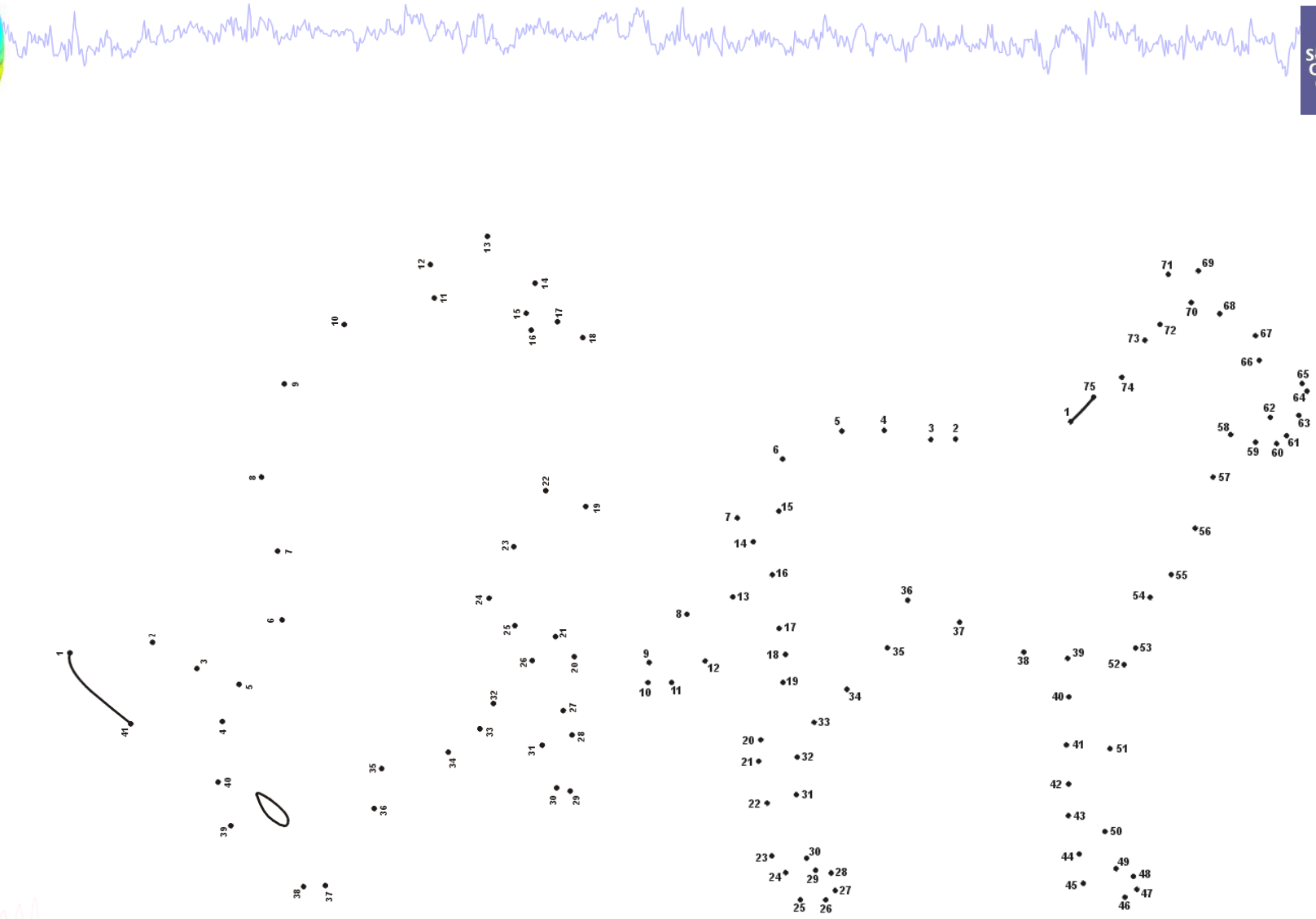


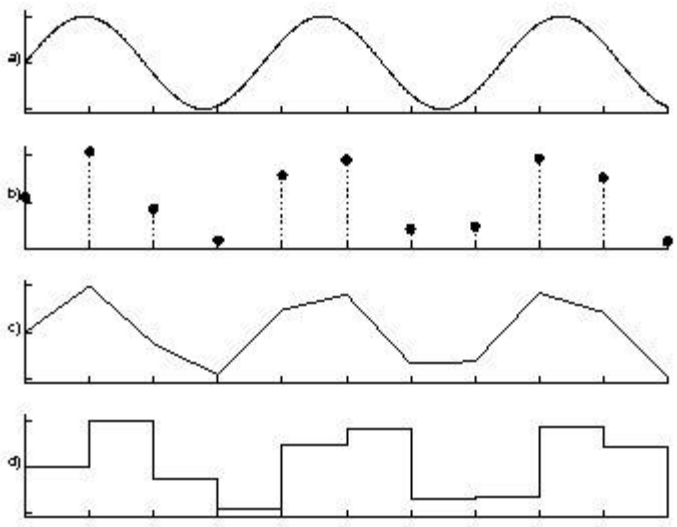
Forward transform $$F(u) = \int_{-\infty}^{+\infty} f(x) e^{-2\pi i u x} dx$$

Inverse transform $$f(x) = \int_{-\infty}^{+\infty} F(u) e^{2\pi i u x} du$$

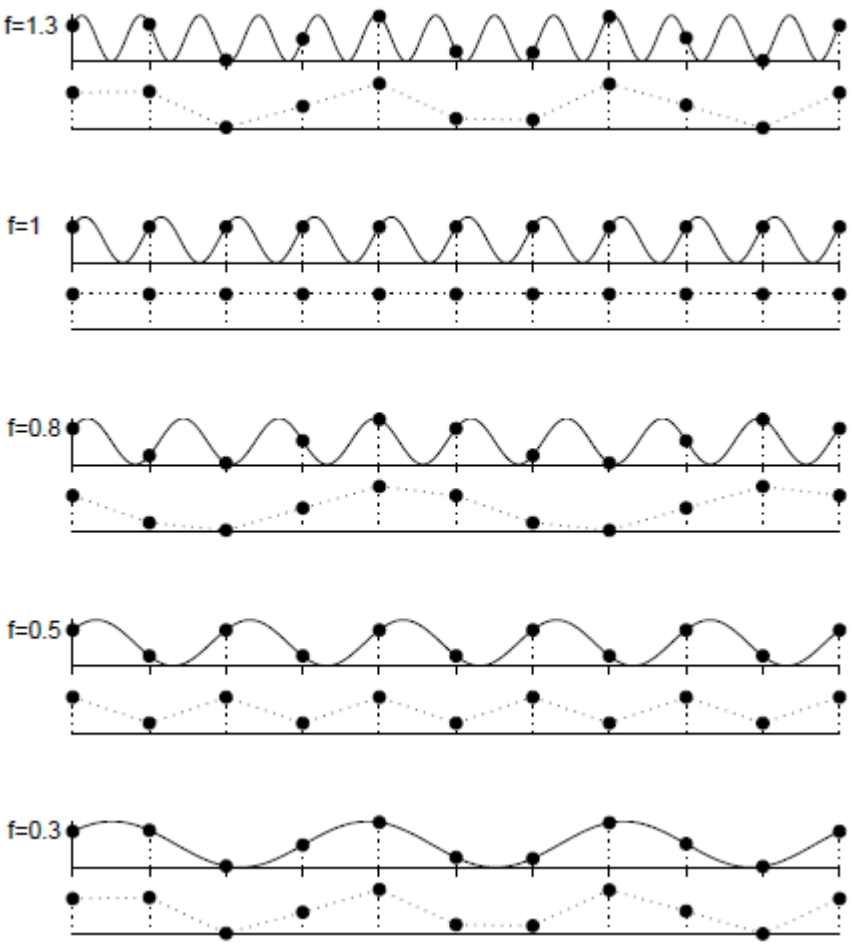
Figure, courtesy of Ravi Ramamoorthi & Wolberg

Sampling





e) 1 1.992 0.751 0.07 1.482 1.81 0.315 0.363 1.844 1.426 0.049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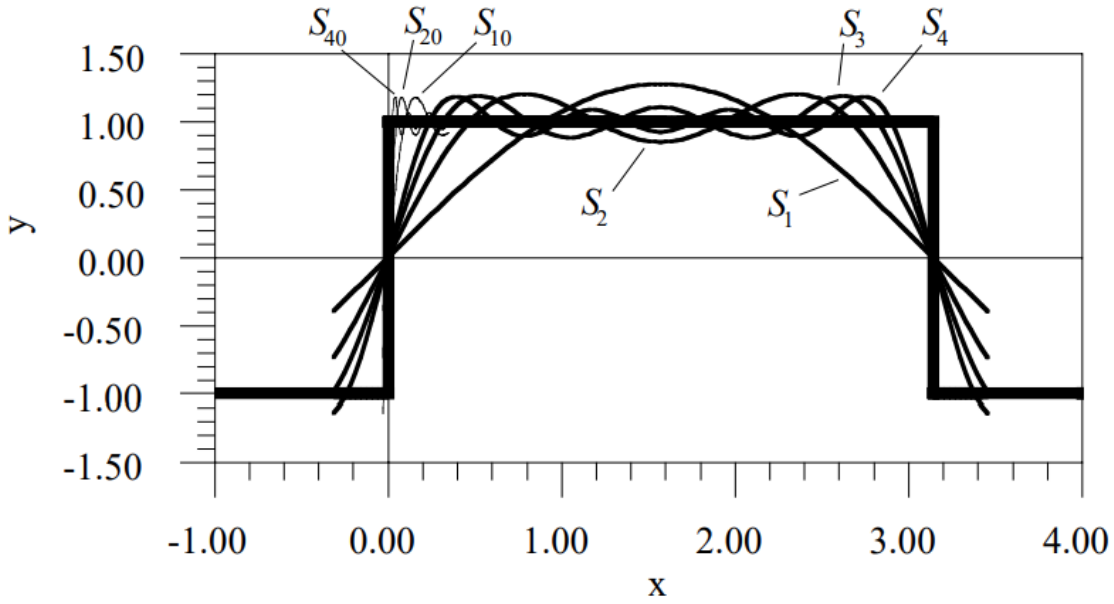
f=0.8
f=0.5
f=0.3


S_{40}
S_{20}
S_{10}
S_3
S_4
S_2
S_1
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
y
-1.00
0.00
1.00
2.00
3.00
4.00
x

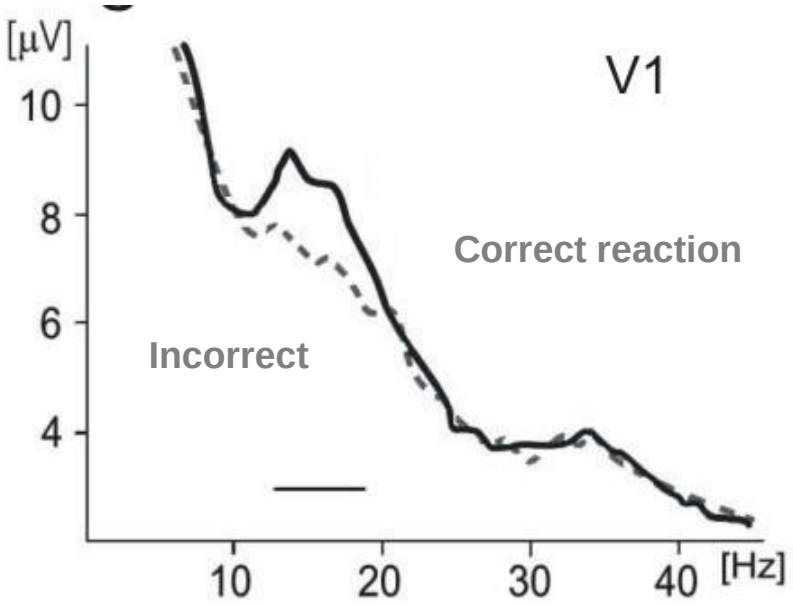
Power Spectrum. Approach 1: FFT

- Why not just take an FFT of our entire signal of interest?
- Advantage – fine frequency resolution
  - ΔF = 1 / signal duration (s)
  - E.g. 100s signal has 0.01 Hz resolution
  - But, do we really need this?

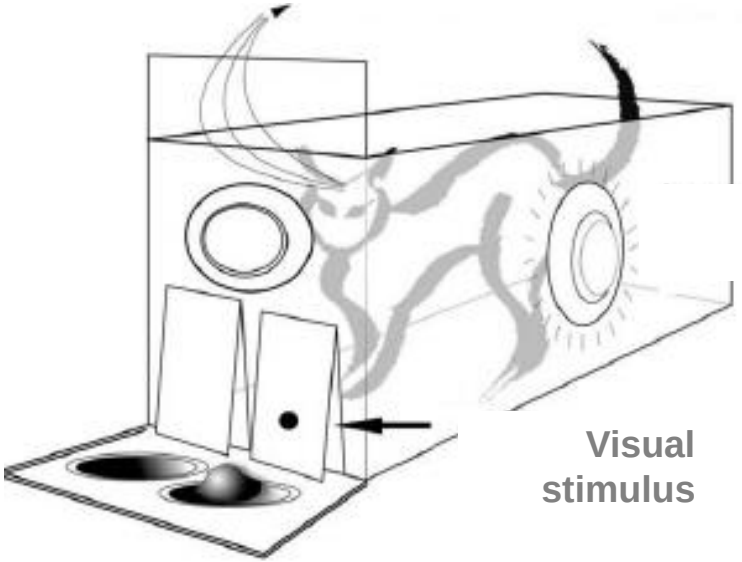
- Disadvantage 1 – high variance
  - Solution: e.g. Welch's method

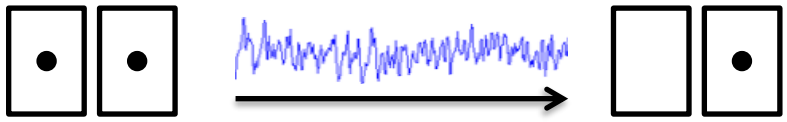
- Disadvantage 2 – no temporal resolution
  - Solution 1: Short-Time Fourier Transform

Beta-band activity & attention



Wróbel et al., 2007





sustain attention or alertness – top down process of preparation for stimulus perception.

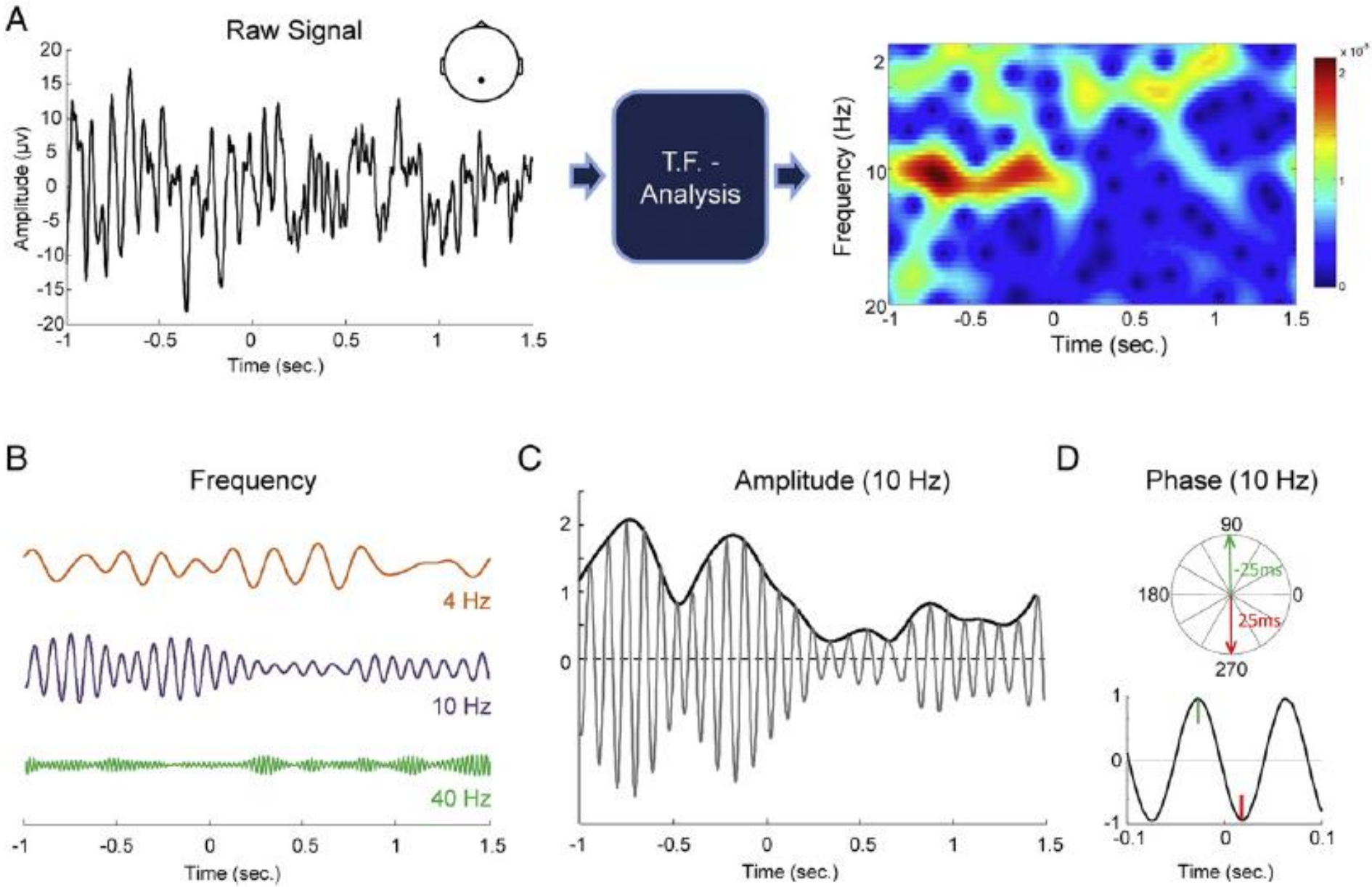
Amplitude and phase

- Power spectra describe the *amount* of a given frequency present. Often expressed in **dB** [$10*\log_{10}(\text{Power})$]

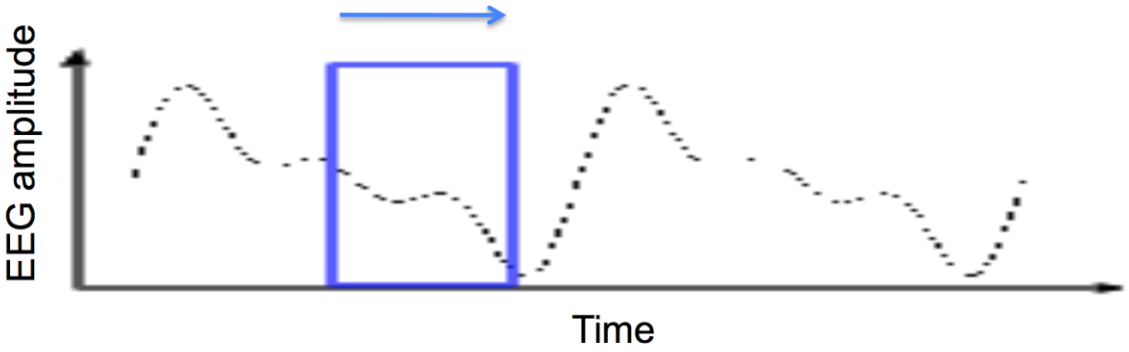
- Power is NOT a complete description of a signal: We also must know the *phase* at each frequency

- FFT/STFT/Wavelet return an amplitude and phase at each time and frequency (represented as complex #).

- To find power, we compute the magnitude, which discards phase.


A
Raw Signal
Amplitude (μv)
Time (sec.)
T.F. - Analysis
Frequency (Hz)
Time (sec.)
B
Frequency
4 Hz
10 Hz
40 Hz
Time (sec.)
C
Amplitude (10 Hz)
Time (sec.)
D
Phase (10 Hz)
90
180
0
270
-25ms
25ms
Time (sec.)

Approach 2: Welch's Method



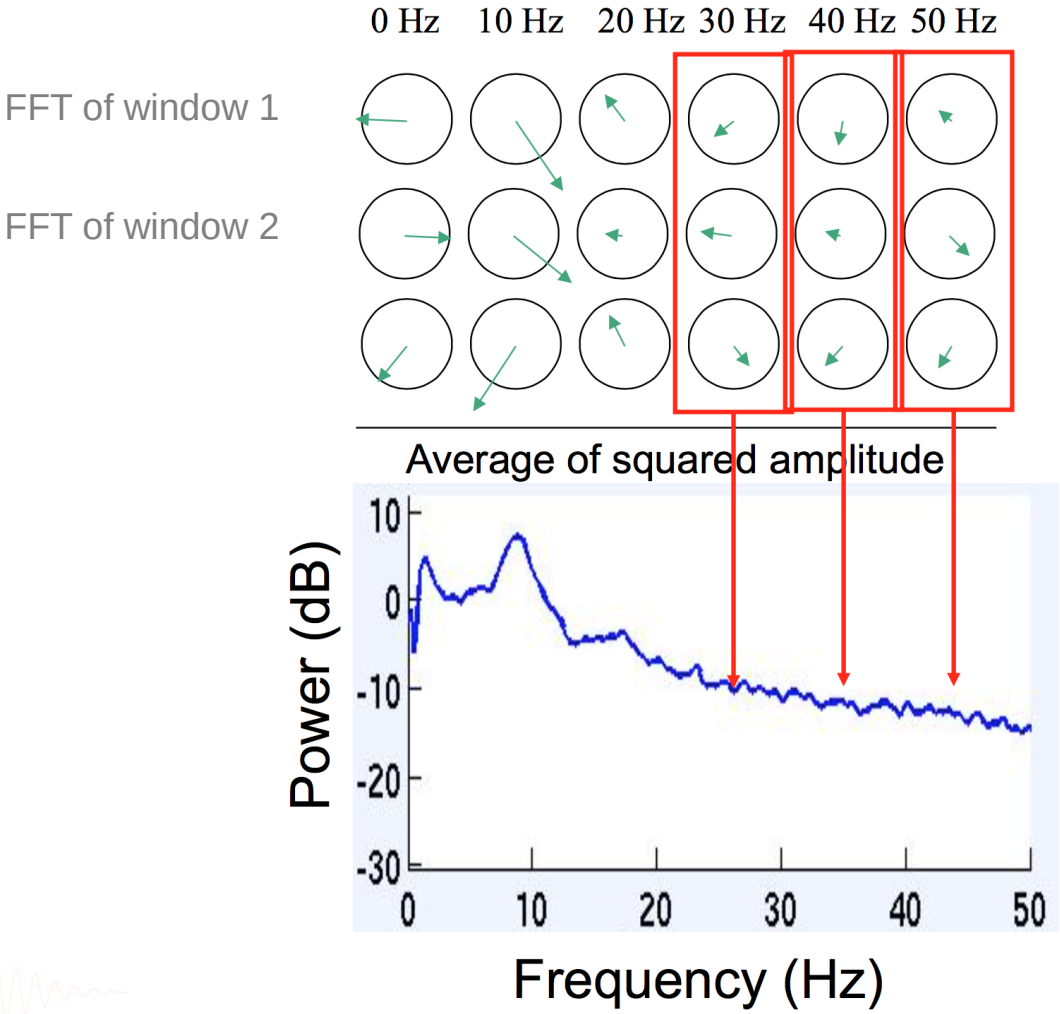
Calculate power spectrum of short signal windows, average.

Advantage: Smoother estimate of power spectrum

Frequency resolution now set by *window* length

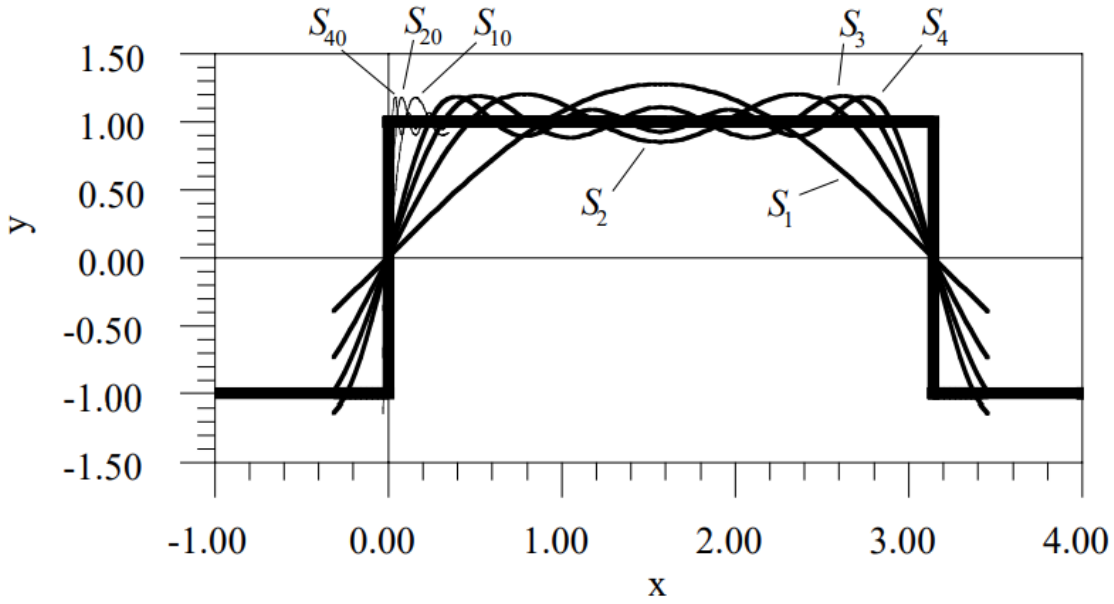
e.g. 1s window -> 1 Hz resolution

In practice: *taper*, don't use rectangular window

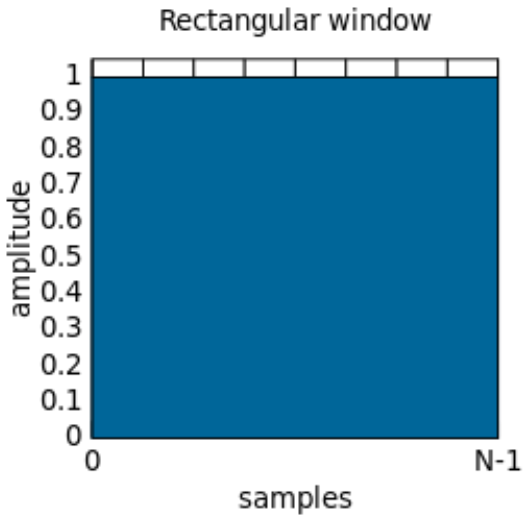

0 Hz
10 Hz
20 Hz
30 Hz
40 Hz
50 Hz
FFT of window 1
FFT of window 2
Average of squared amplitude
Power (dB)
10
0
-10
-20
-30
0
10
20
30
40
50
Frequency (Hz)

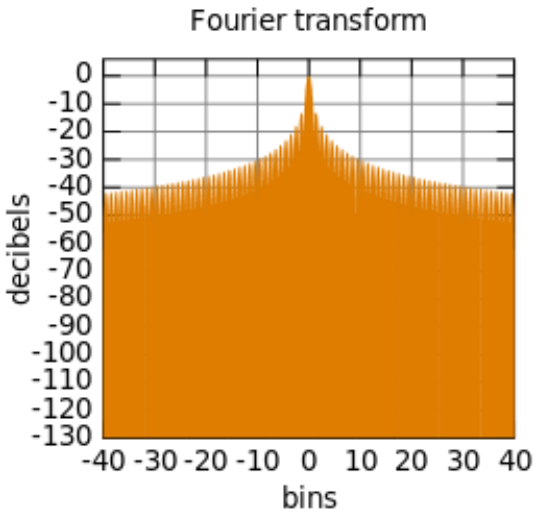
Windowing

- When we pick a short segment of signal, we typically window it with a smooth function (taper).
- Windowing in time = convolving (filtering) the spectrum with the Fourier transform of the window
- No window (=rectangular window) results in the most smearing of the spectrum
- There are many other windows optimized for different purposes: Hamming, Gaussian…


S_{40}
S_{20}
S_{10}
S_3
S_4
S_2
S_1
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
y
-1.00
0.00
1.00
2.00
3.00
4.00
x

Windows and their Fourier transforms

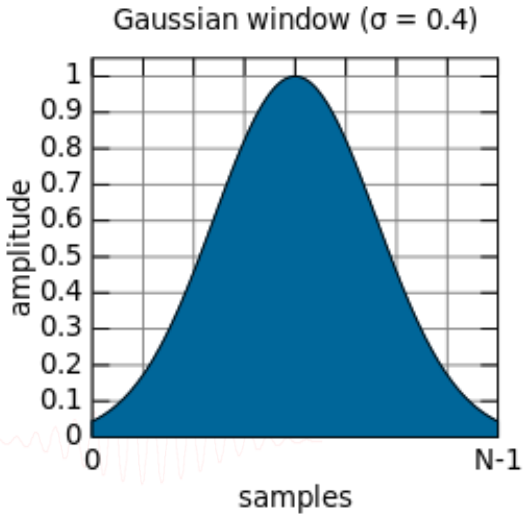


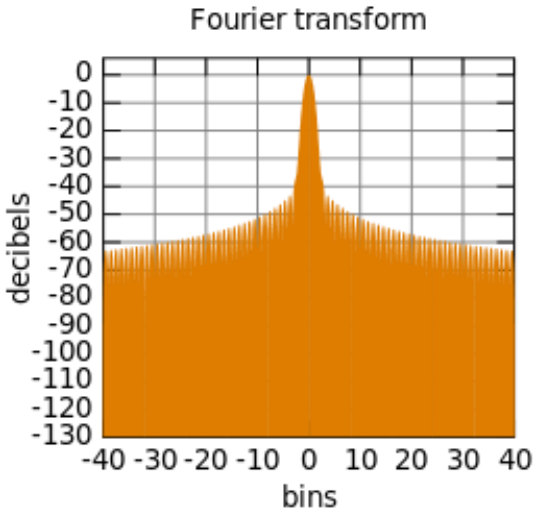


Narrowest main peak, but

Highest side-lobes

Most spectral 'smearing'

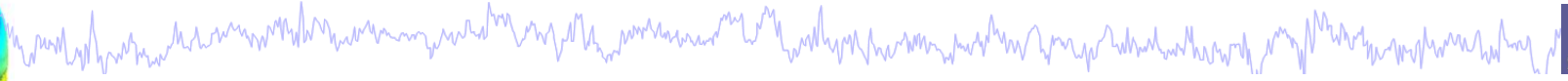


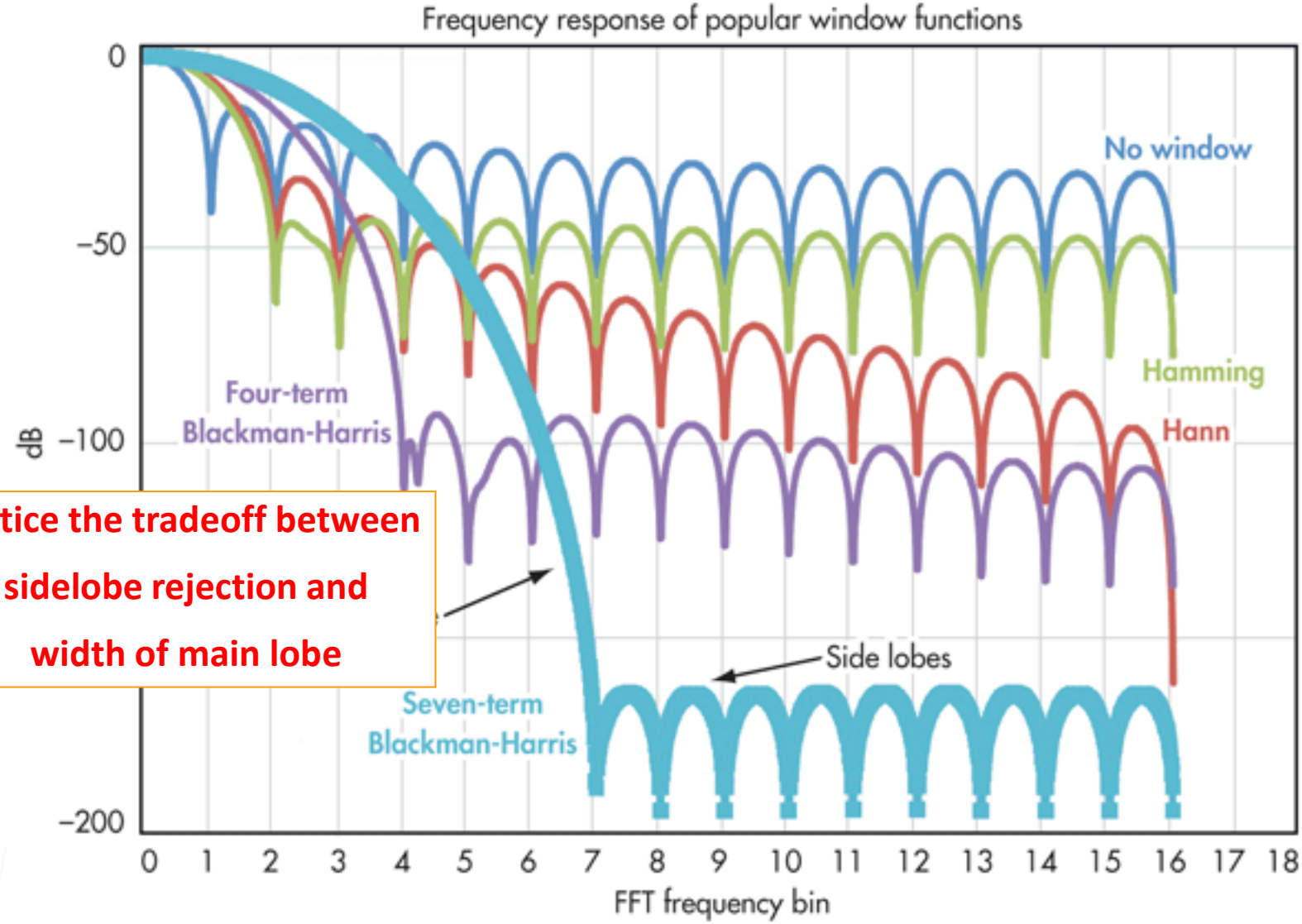


Wider main peak, but

much lower side-lobes

Close-up view



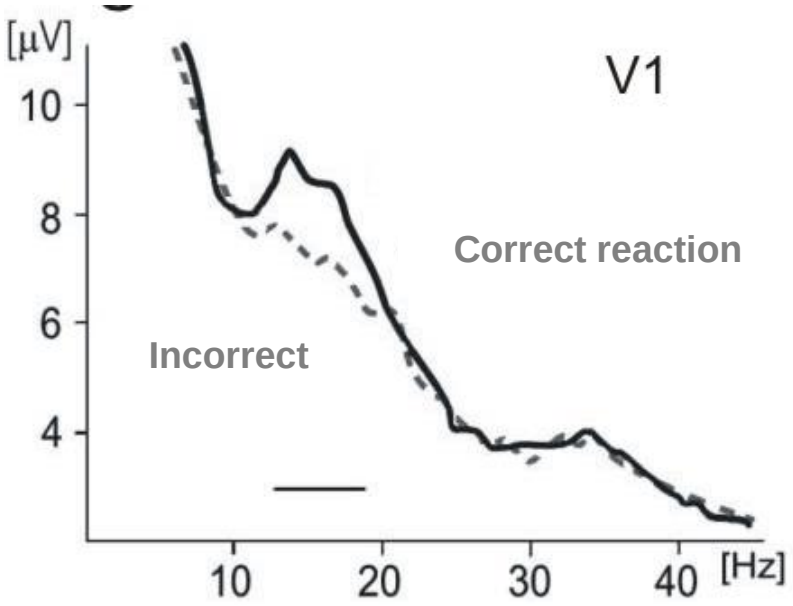


Notice the tradeoff between sidelobe rejection and width of main lobe

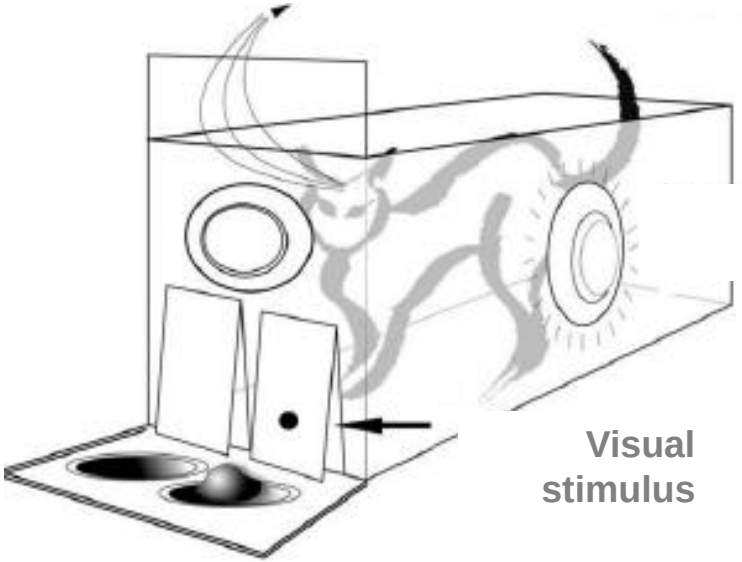
Part 2: Time-Frequency Analysis

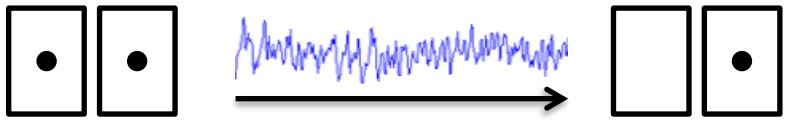
- Short-Time Fourier Transform
  - Find power spectrum of short windows
  - “Spectrogram”
- Advantage: Can visualize time-varying frequency content
- Disadvantage: Fixed temporal resolution is not optimal

Beta-band activity & attention



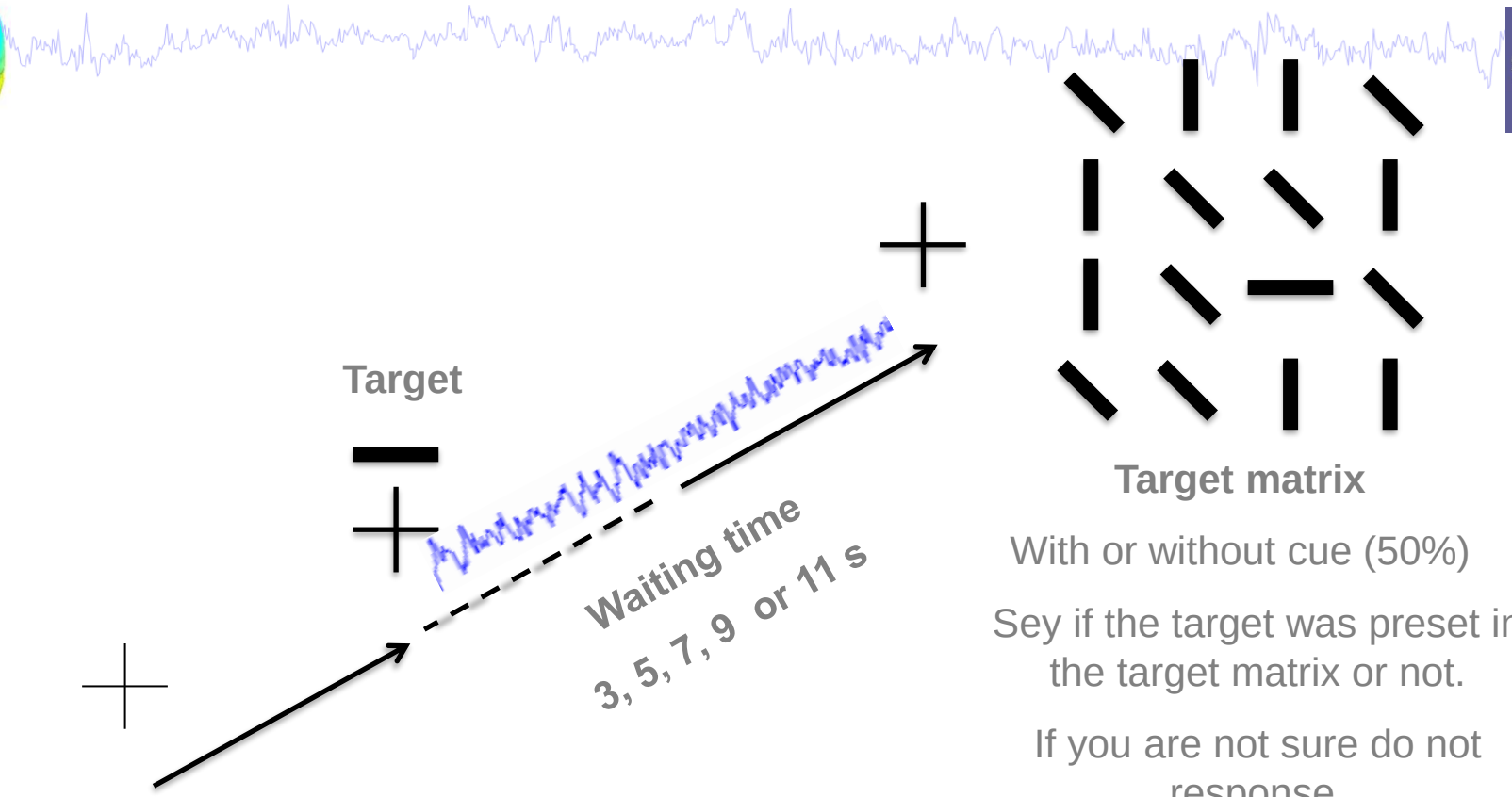
Wróbel et al., 2007





sustain attention or alertness – top down process of preparation for stimulus perception.

Procedure



Target matrix

With or without cue (50%)

Sey if the target was preset in the target matrix or not.

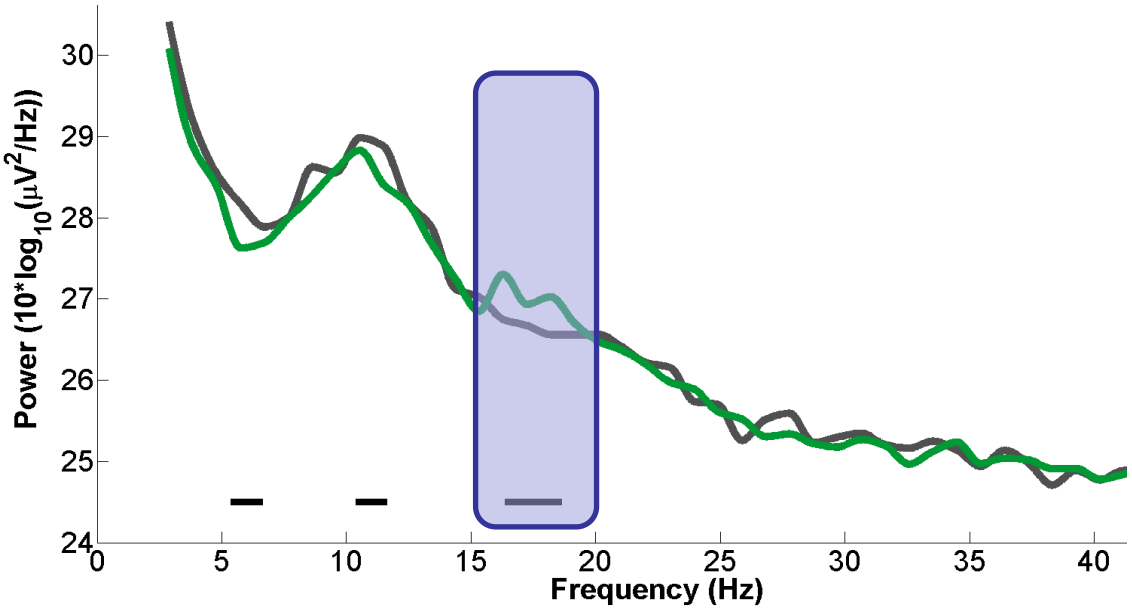
If you are not sure do not response.

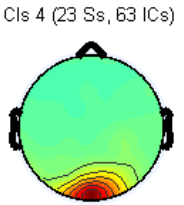
Self addapting time of presentation:

- 5% after correct response

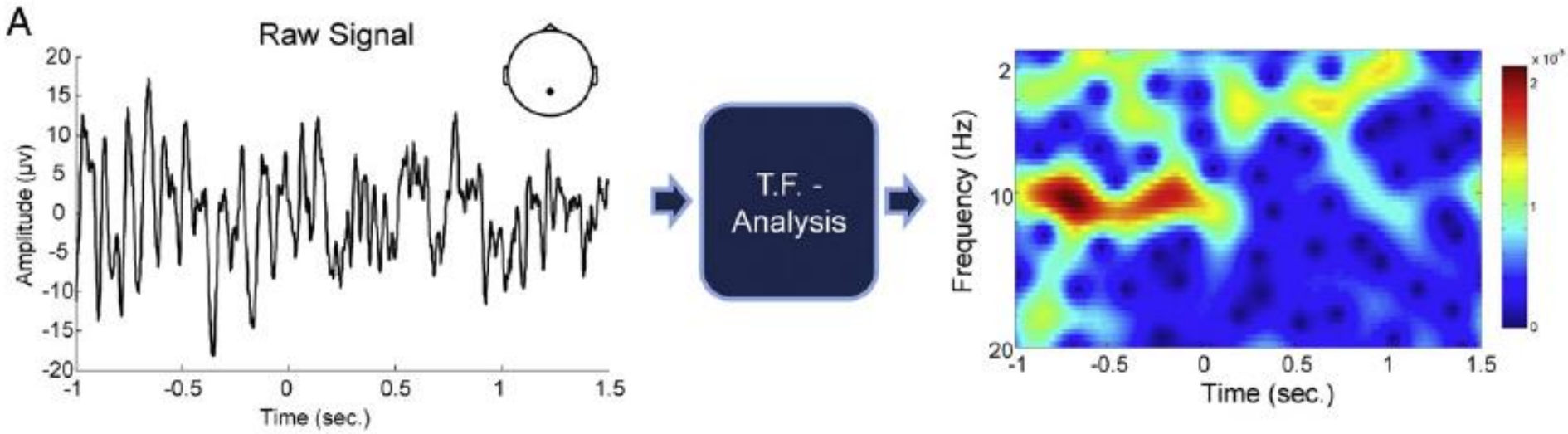
+ 10% after incorrect response

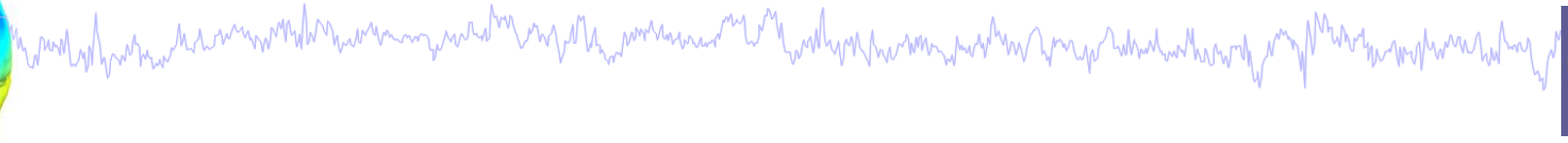
Gola et al., 2013



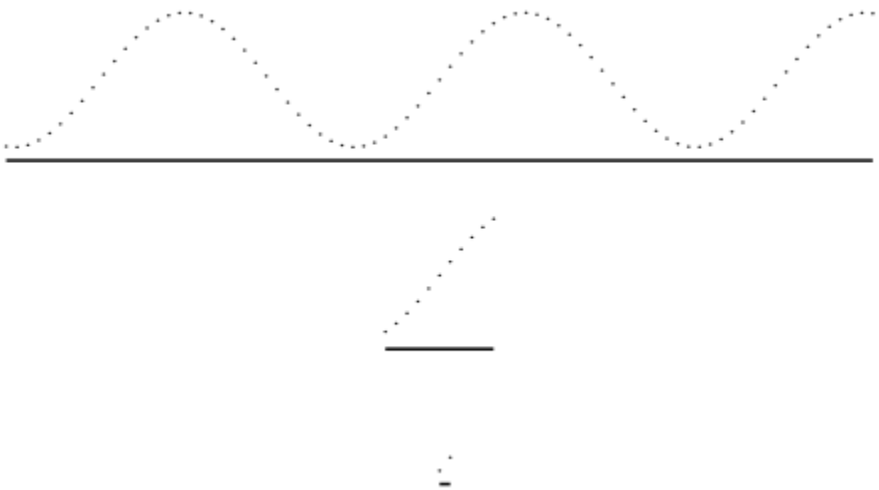


Gola et al., 2013


A
Raw Signal
Amplitude (μv)
Time (sec.)
T.F. - Analysis
Frequency (Hz)
Time (sec.)

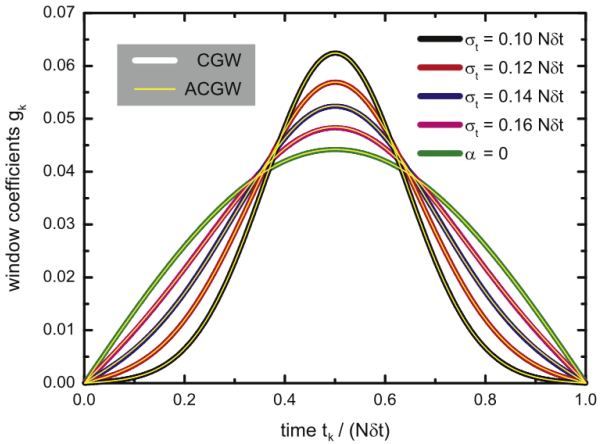


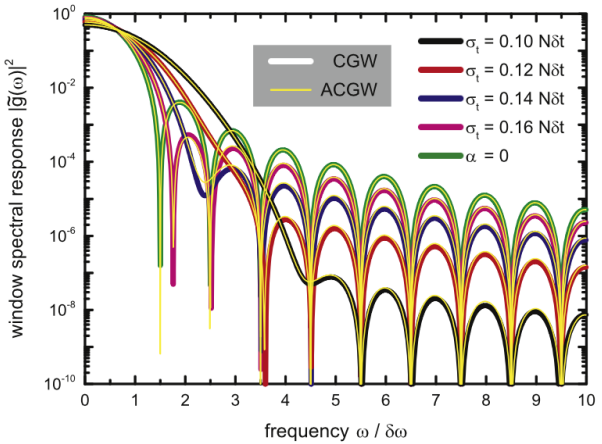
Haisenberg Uncertainty



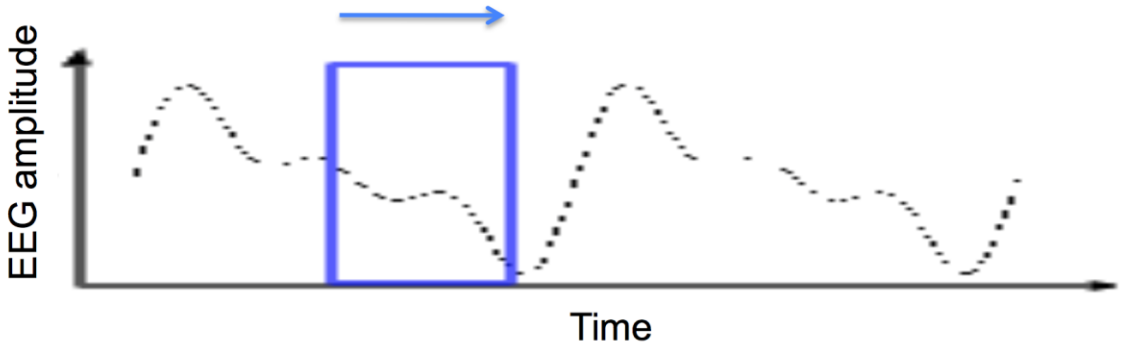
Time-Frequency Uncertainty

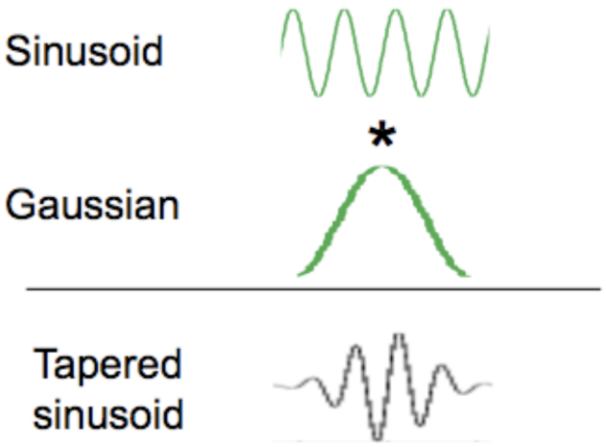
- You cannot have both arbitrarily good temporal and frequency resolution!
  - $\sigma_t * \sigma_f \geq 1/2$
- If you want sharper temporal resolution, you will sacrifice frequency resolution, and vice versa.
- (Optimal: Confined Gaussian)





Starosielec S, Hägele D (2014) Discrete-time windows with minimal RMS bandwidth for given RMS temporal width. Signal Processing 102:240–6.





For each time point

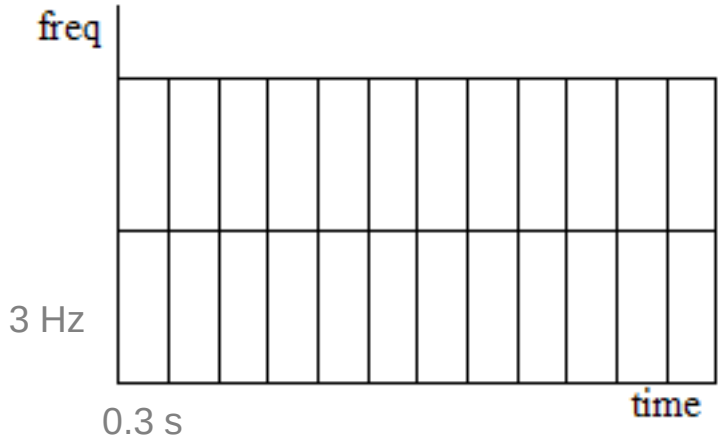
Analyze signal using the wavelets

for different frequencies.

Consequence for STFT

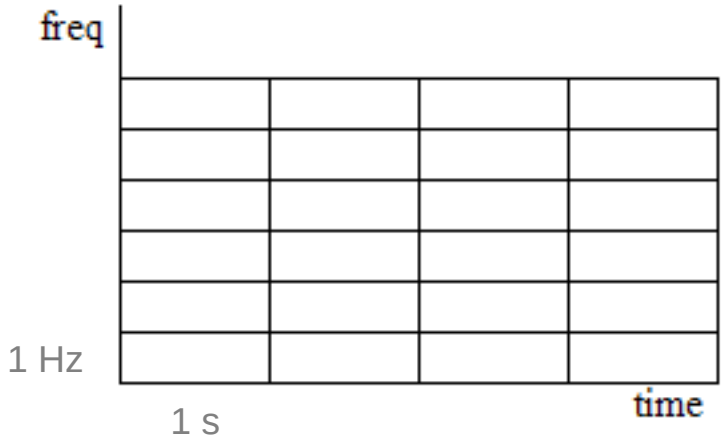
Shorter Windows

poorer frequency resolution



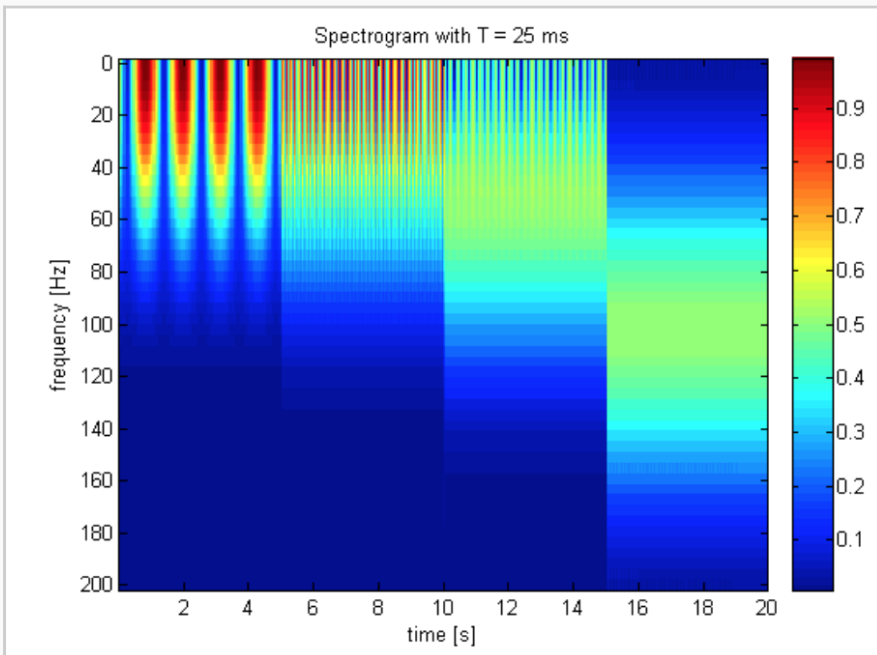
Longer Windows

finer frequency resolution

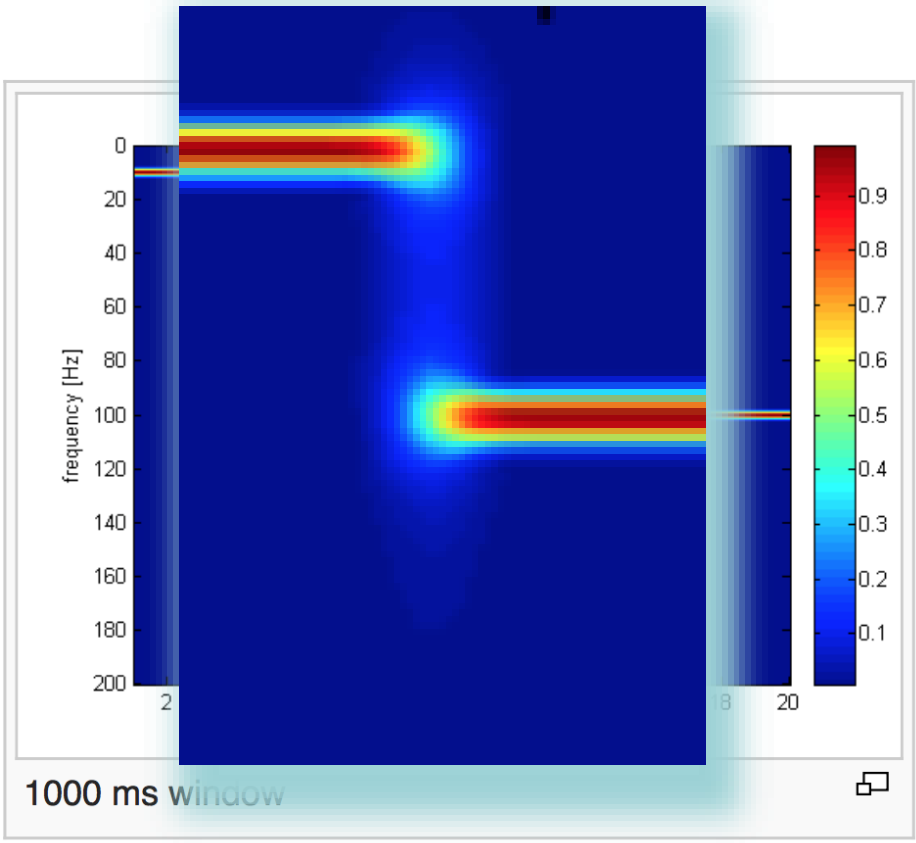


Time-Frequency Tradeoff

Signal: 10, 25, 50, 100 Hz



25 ms window



1000 ms window

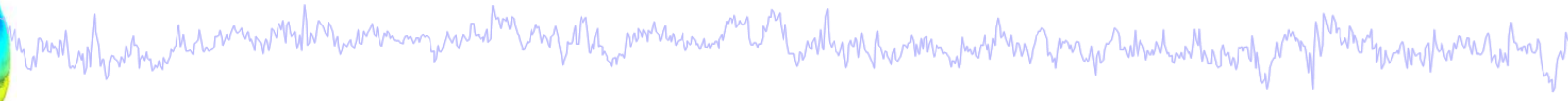
One better way: Wavelet transform

- Wavelet transform is a ‘multi-resolution’ time-frequency decomposition.

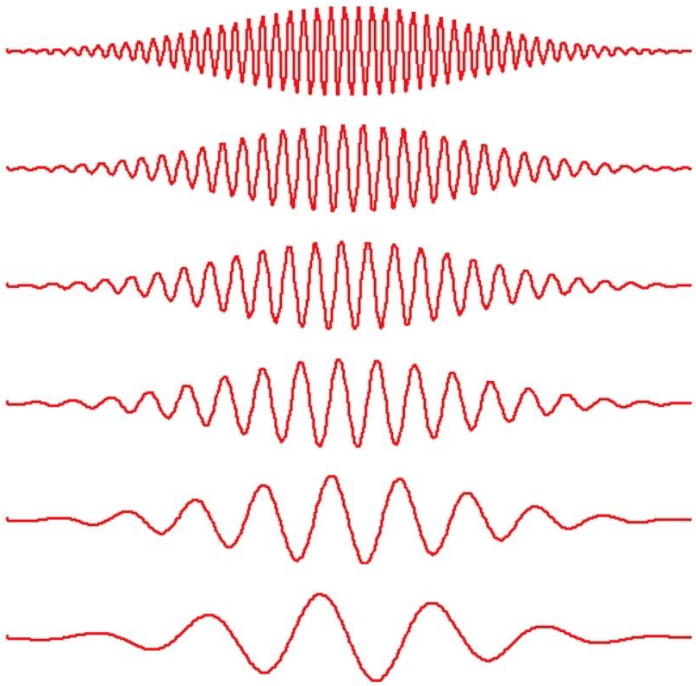
- Intuition: Higher frequency signals have a faster time scale

- So, vary window length with frequency!
  - longer window at lower frequencies
  - shorter window at higher frequencies

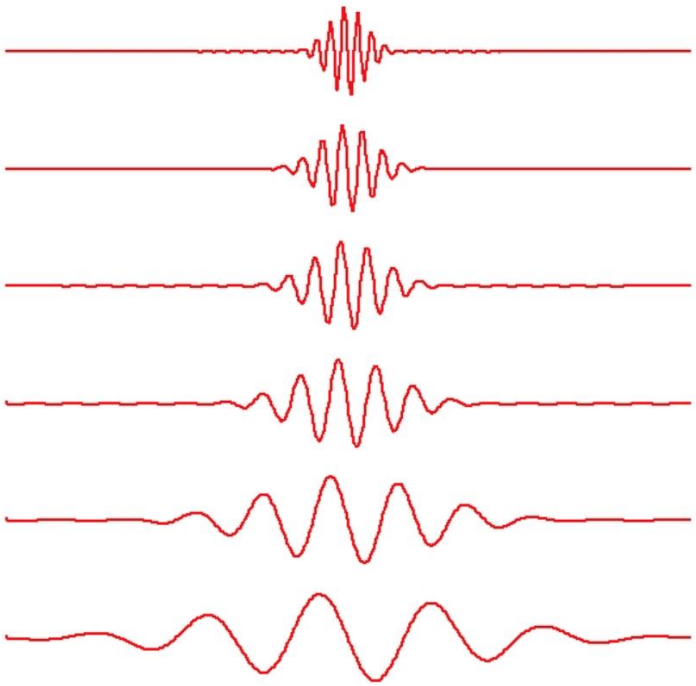
Comparison of FFT & Wavelet



FFT

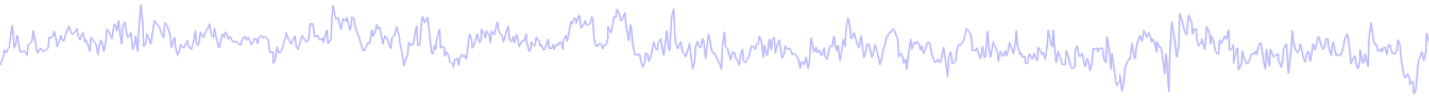


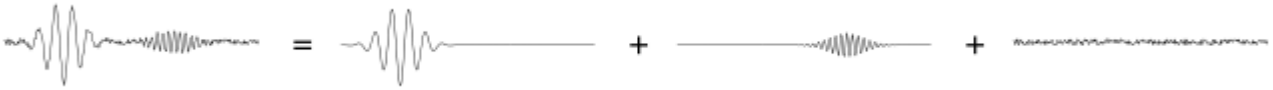
Wavelet

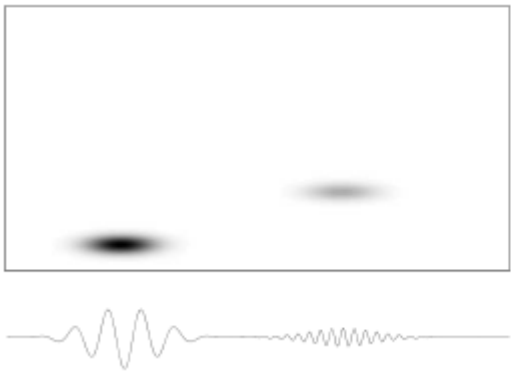


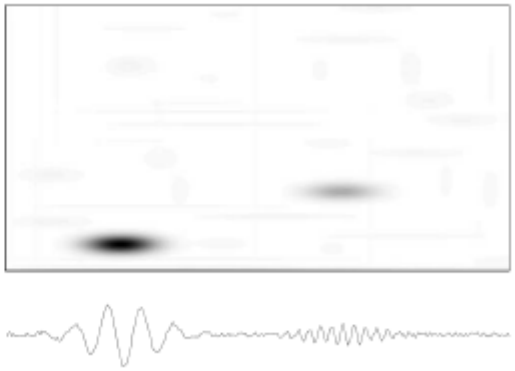
Scaled versions of one shape

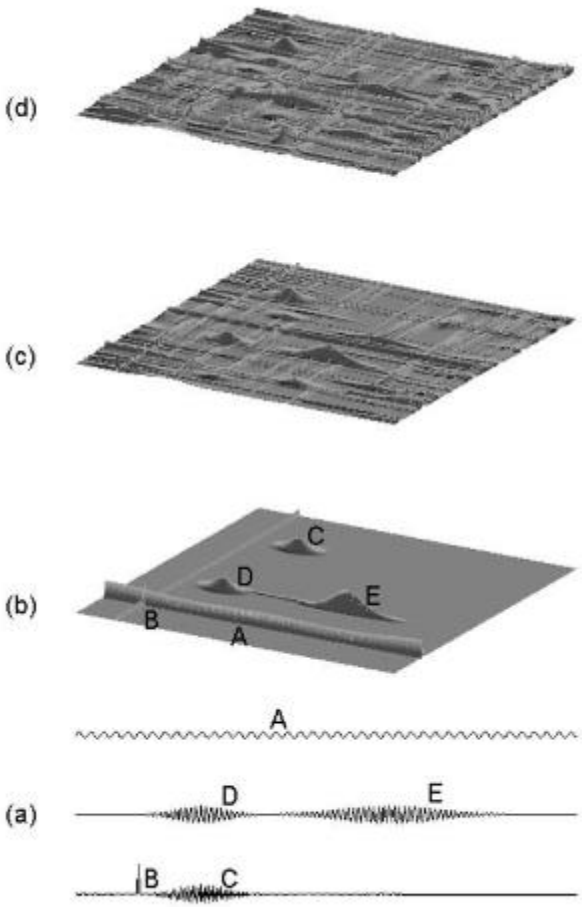
Constant number of cycles

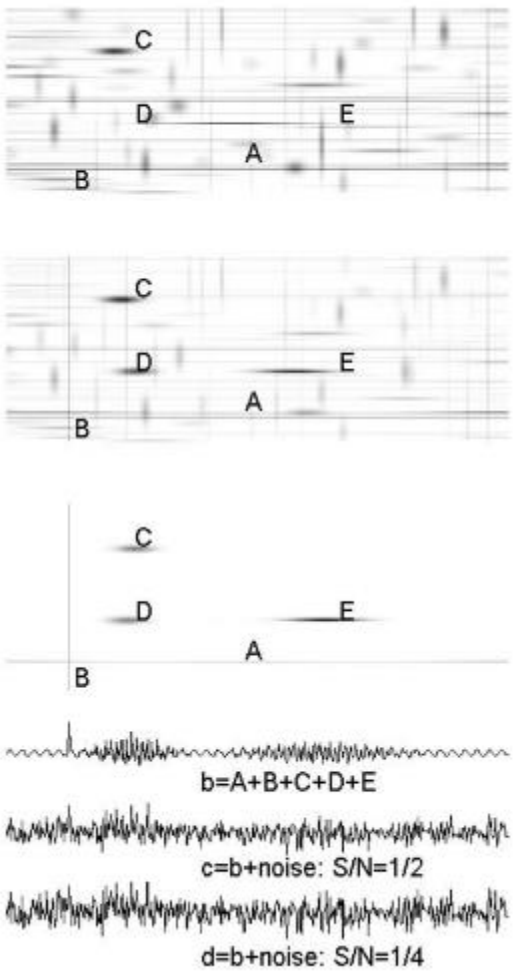


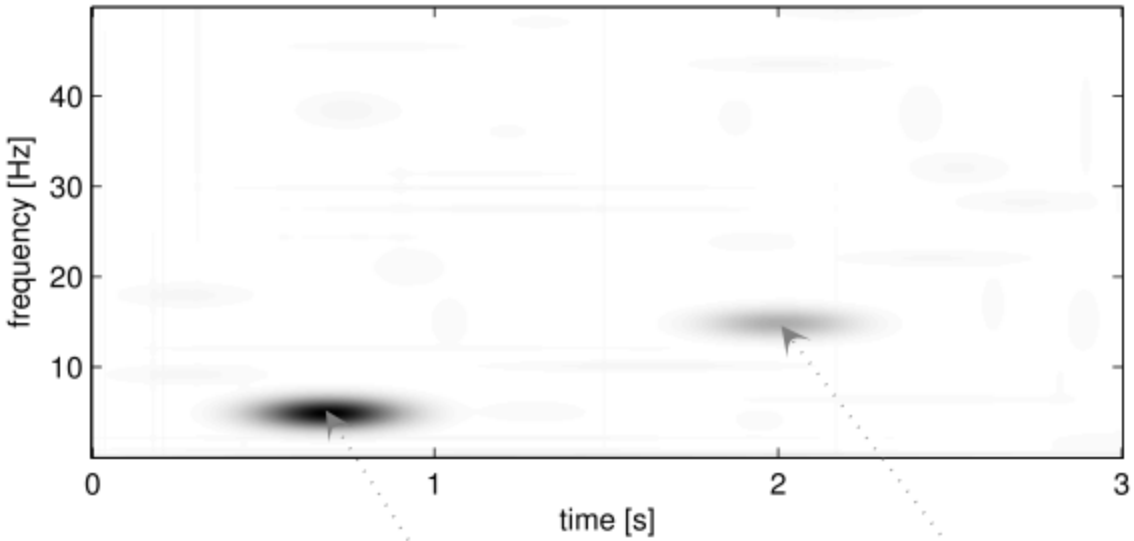


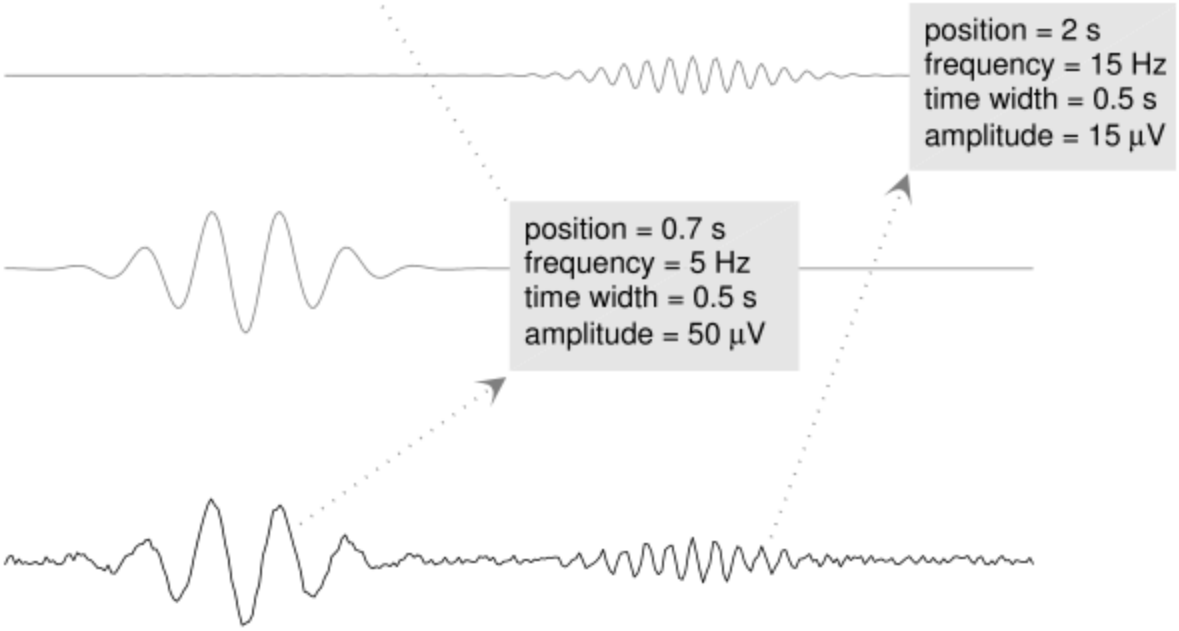





(d)
(c)
(b)
(a)
A
B
C
D
E

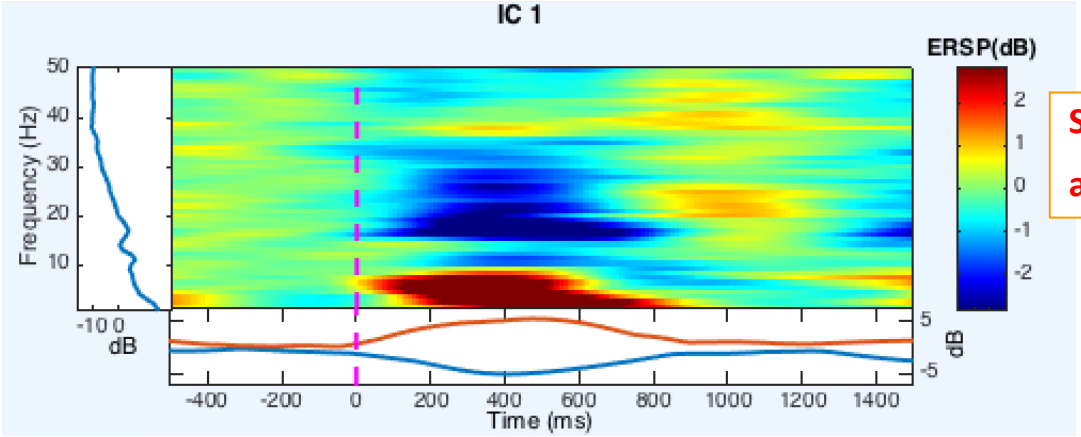

C
D
E
A
B
b=A+B+C+D+E
c=b+noise: S/N=1/2
d=b+noise: S/N=1/4


frequency [Hz]
40
30
20
10
0
1
2
3
time [s]


position = 2 s
frequency = 15 Hz
time width = 0.5 s
amplitude = 15 µV
position = 0.7 s
frequency = 5 Hz
time width = 0.5 s
amplitude = 50 µV

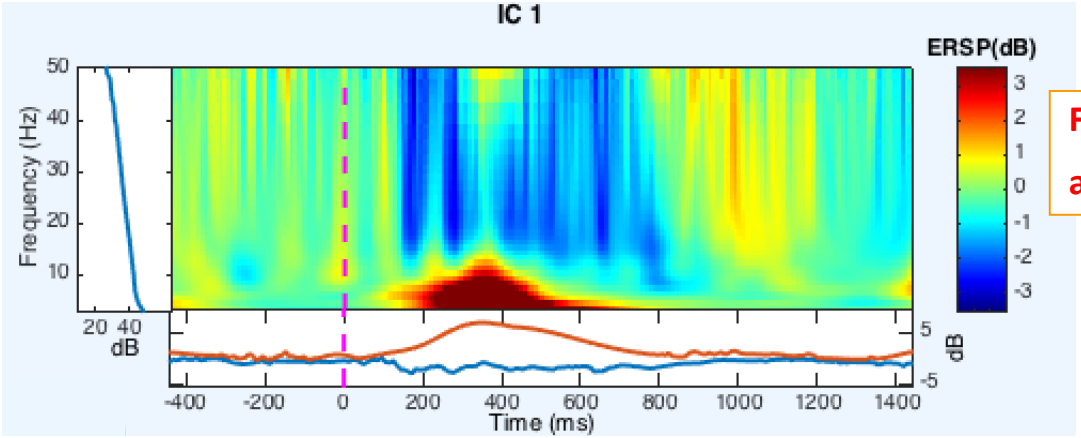
Comparison of FFT & Wavelet

FFT



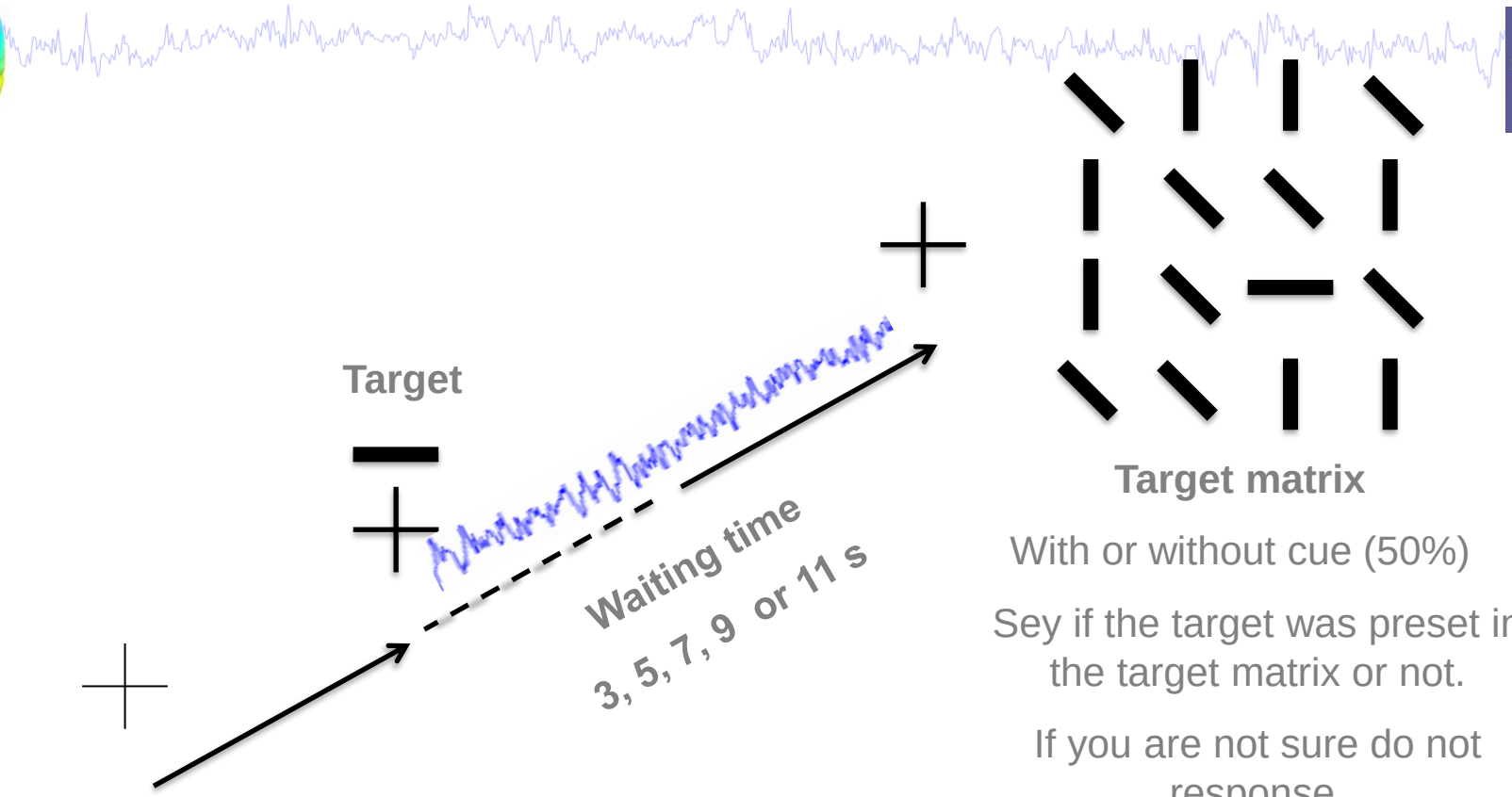
Similar time resolution across frequencies

Wavelet



Finer time resolution at high frequencies

Procedure



Target matrix

With or without cue (50%)

Sey if the target was preset in the target matrix or not.

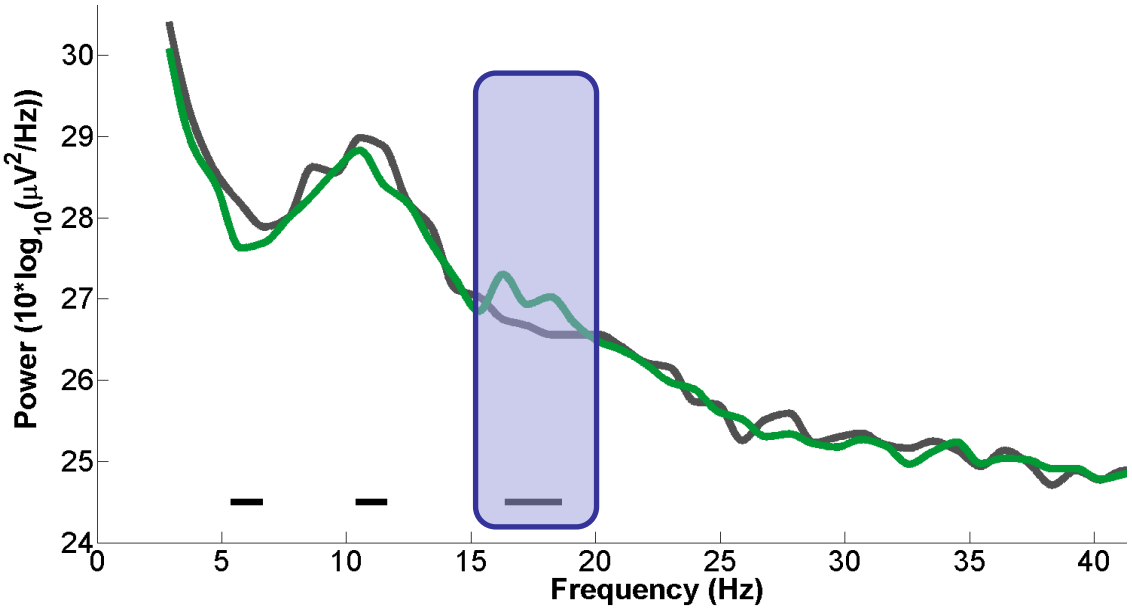
If you are not sure do not response.

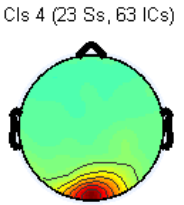
Self addapting time of presentation:

- 5% after correct response

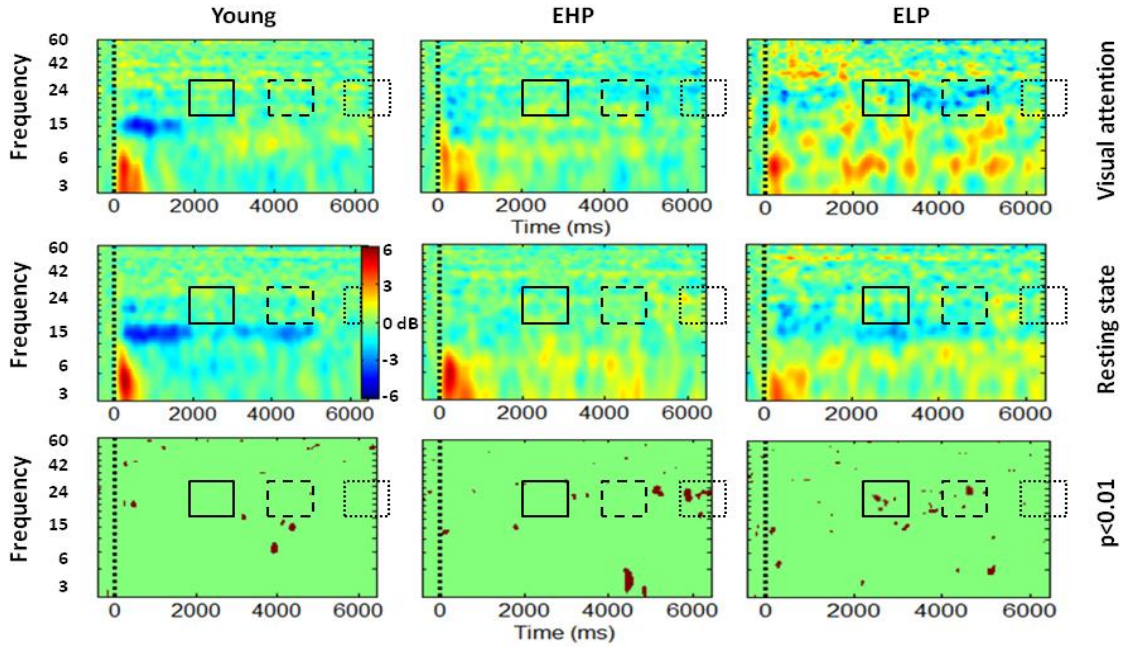
+ 10% after incorrect response

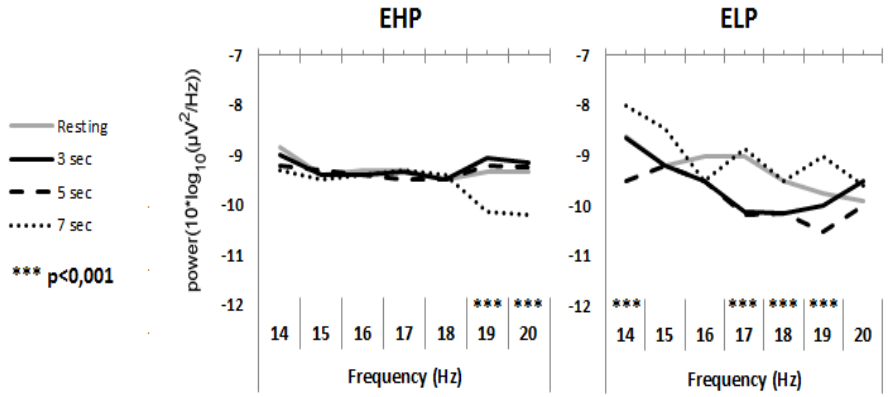
Gola et al., 2013

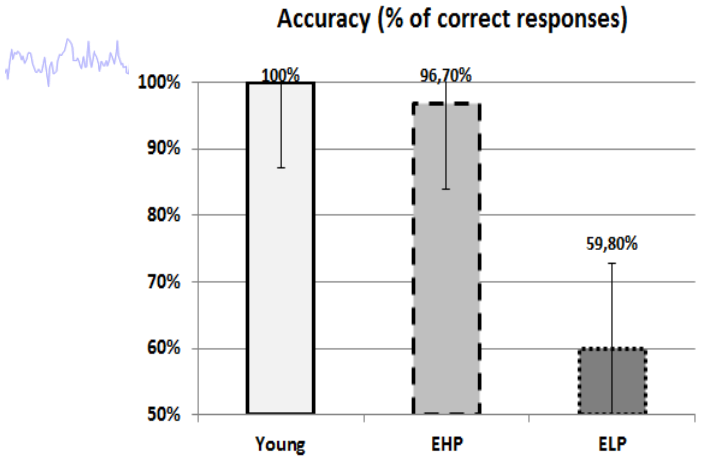


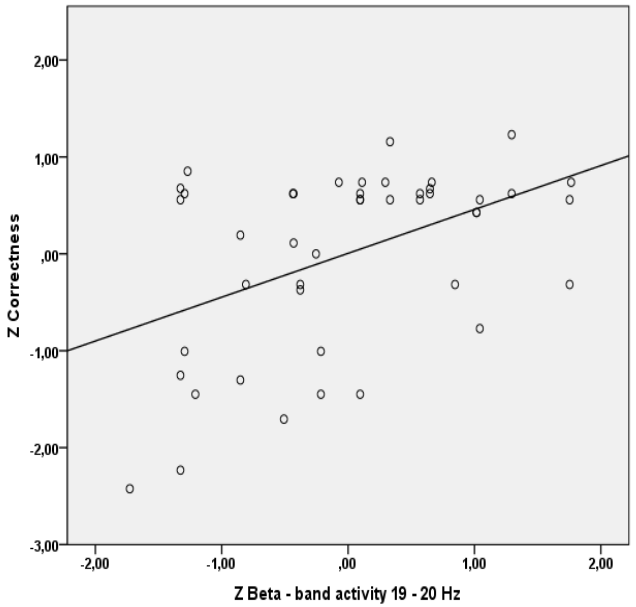


Gola et al., 2013





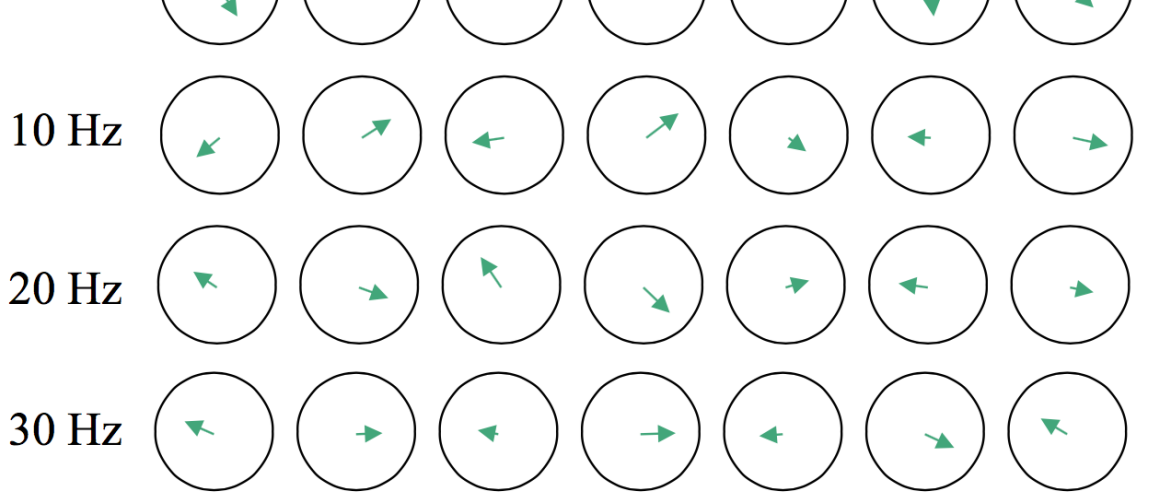




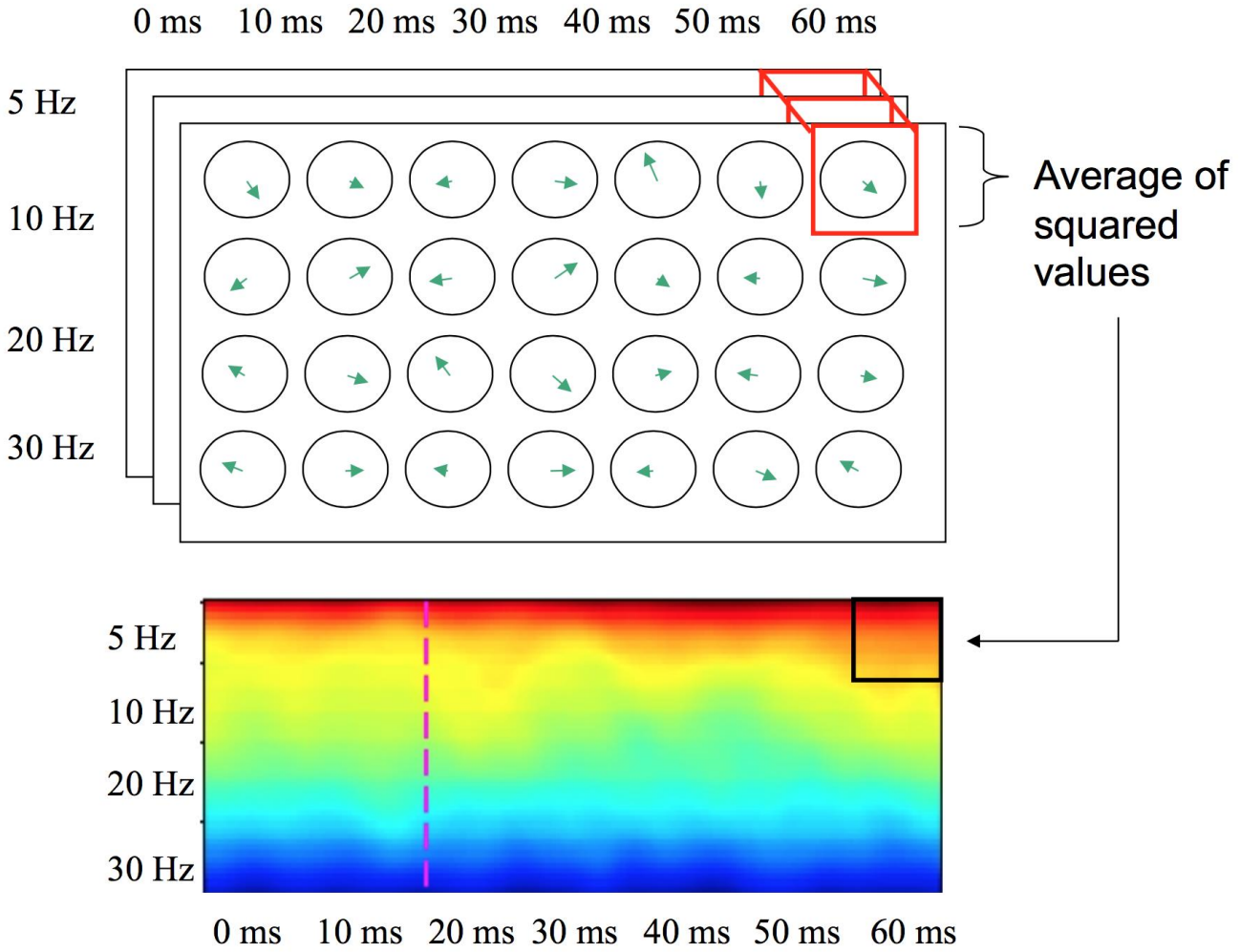
Gola et al., 2012

r = 0.456; p<0.01

Spectrogram of one epoch of data



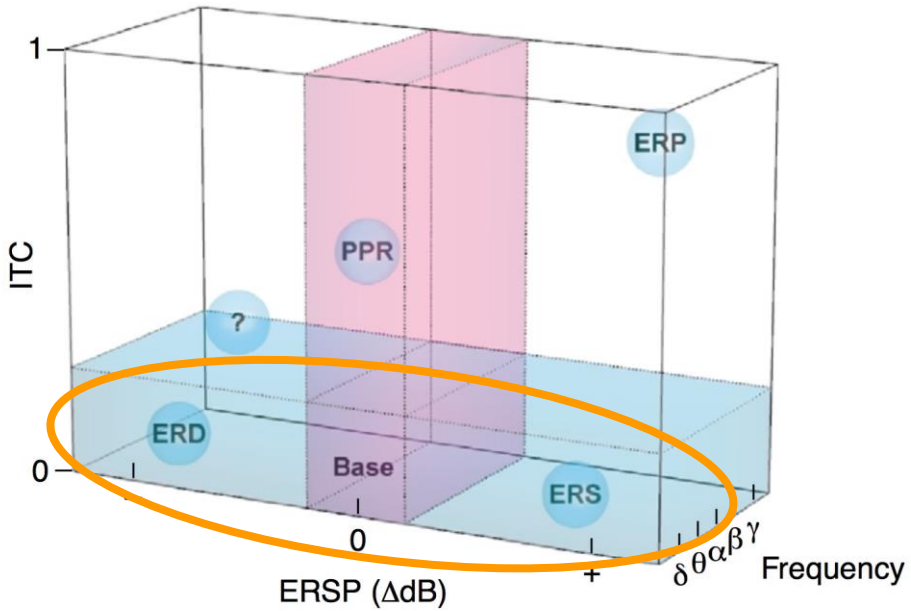
Computing Spectrogram Power



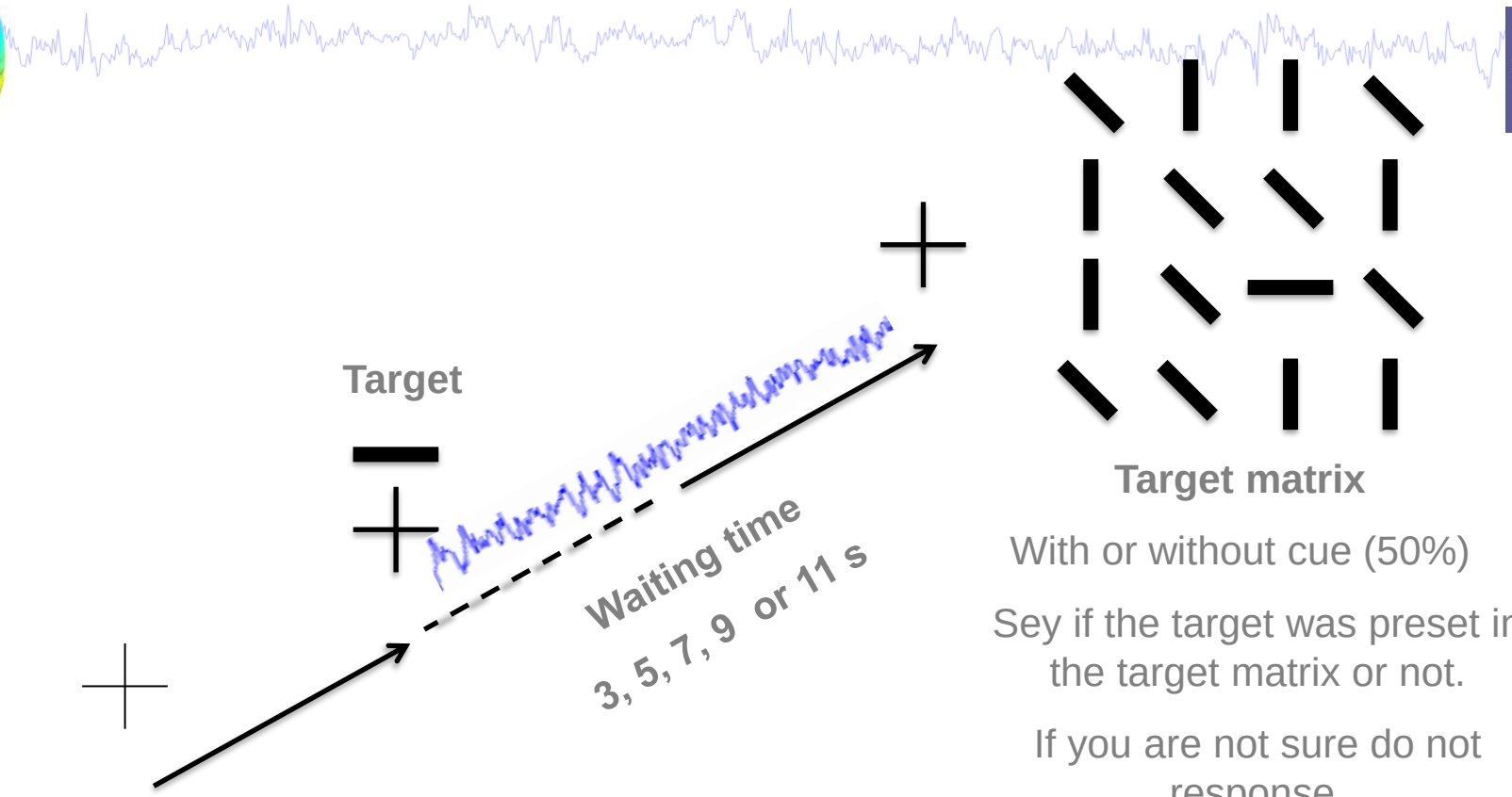
Definition: ERSP

- Event Related Spectral Perturbation

- Change in power in different frequency bands relative to a baseline. ERS (Event-Related *Synchronization*), ERD (Event-Related *Desynchronization*)



Procedure



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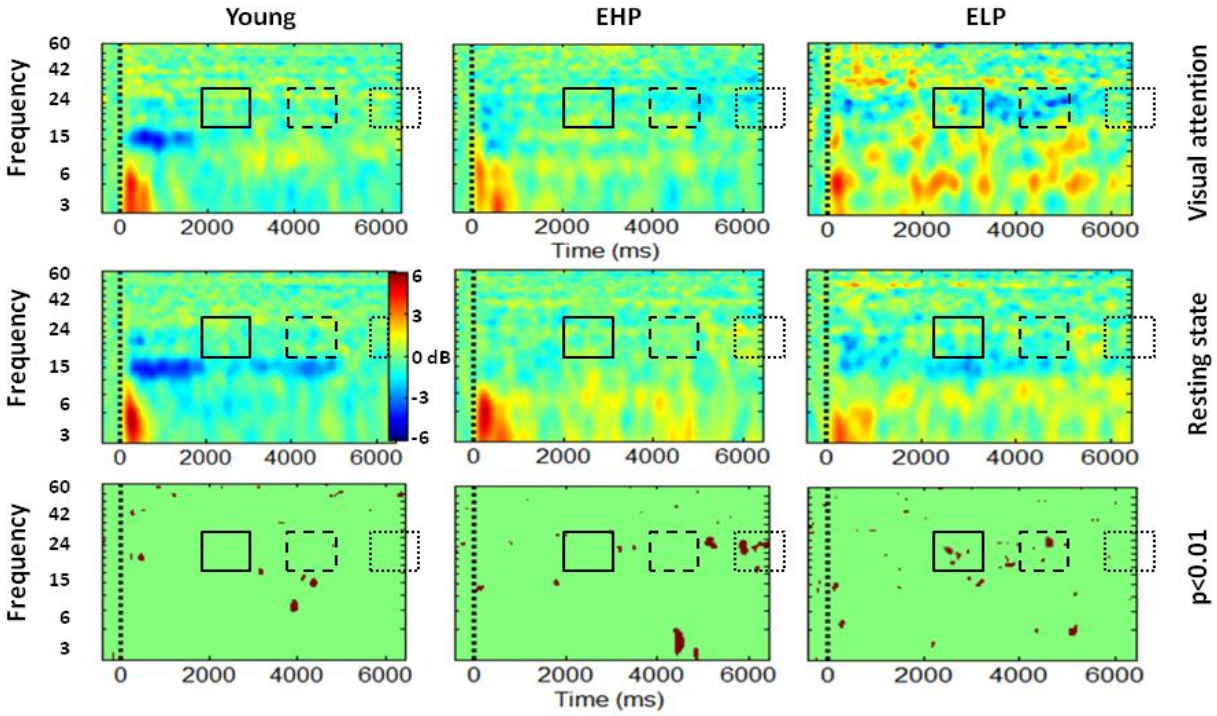
Gola et al., 2013



Gola et al., 2012

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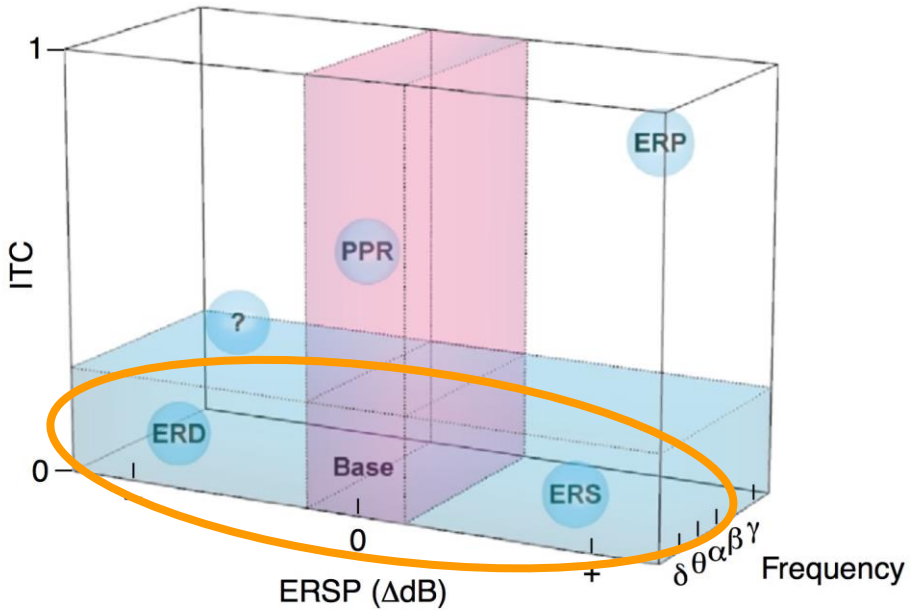
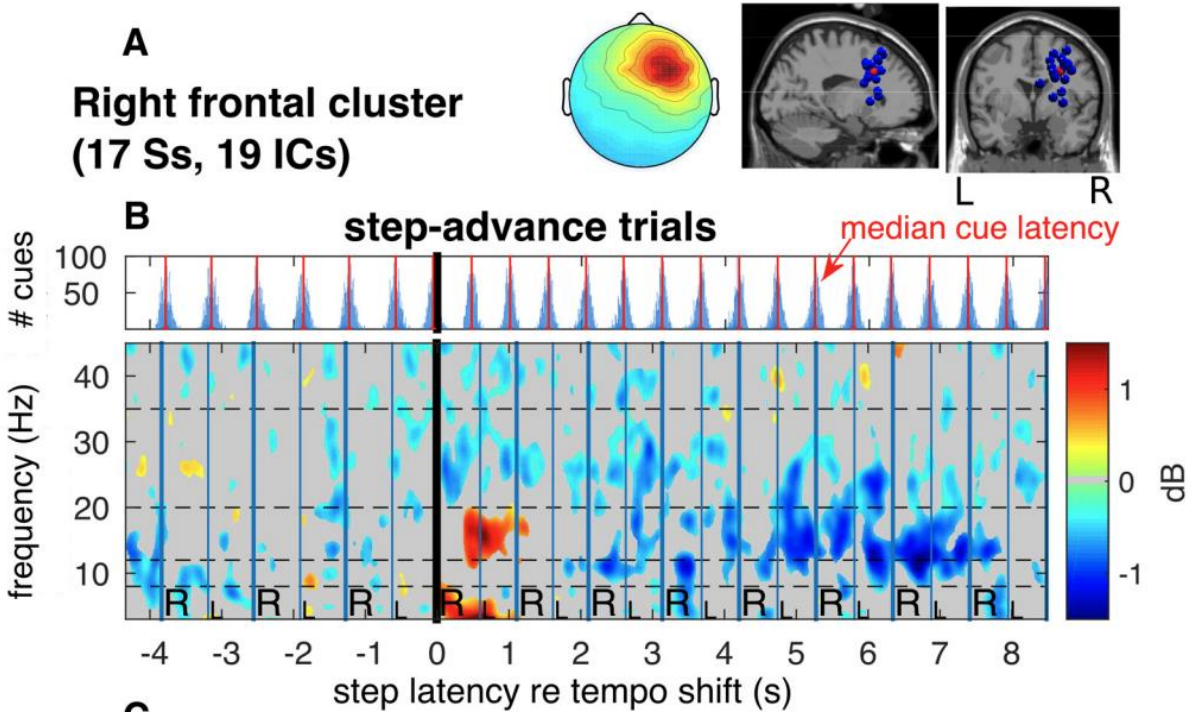
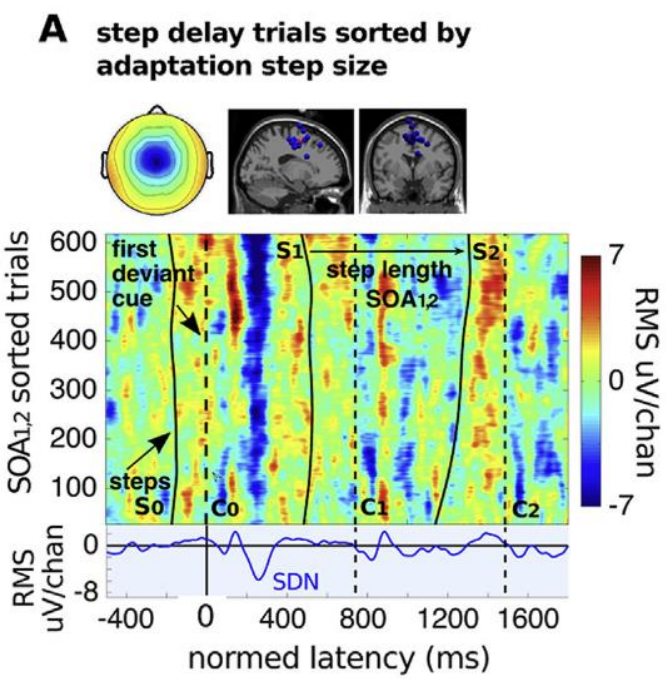
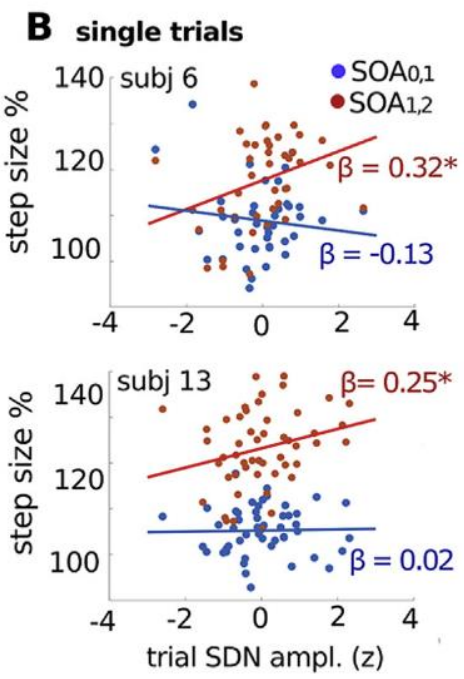
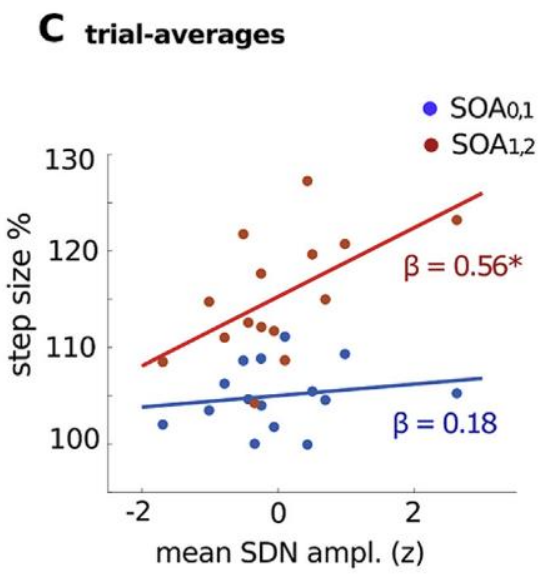




Wagner et al., 2016

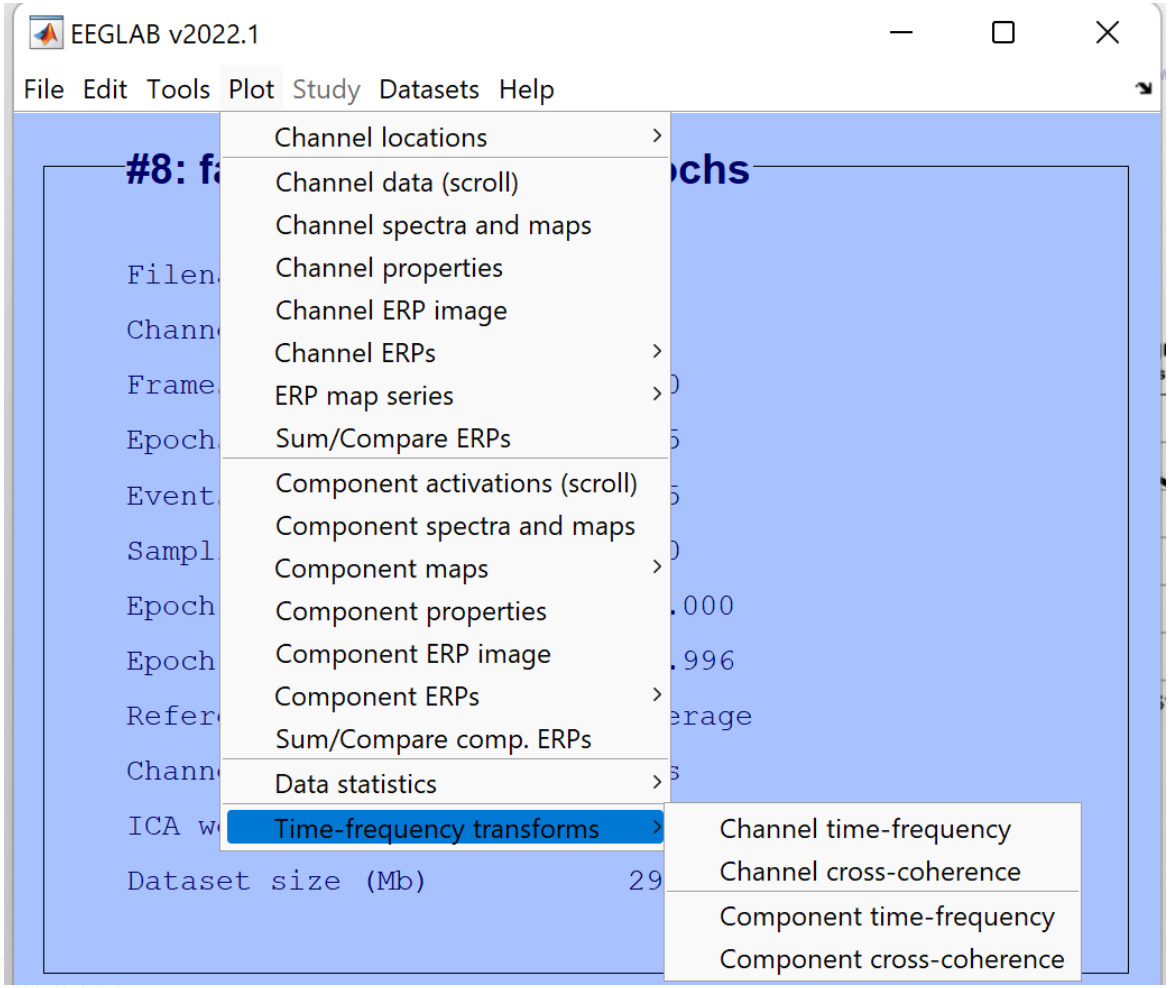






Wagner et al., 2019

Try it out

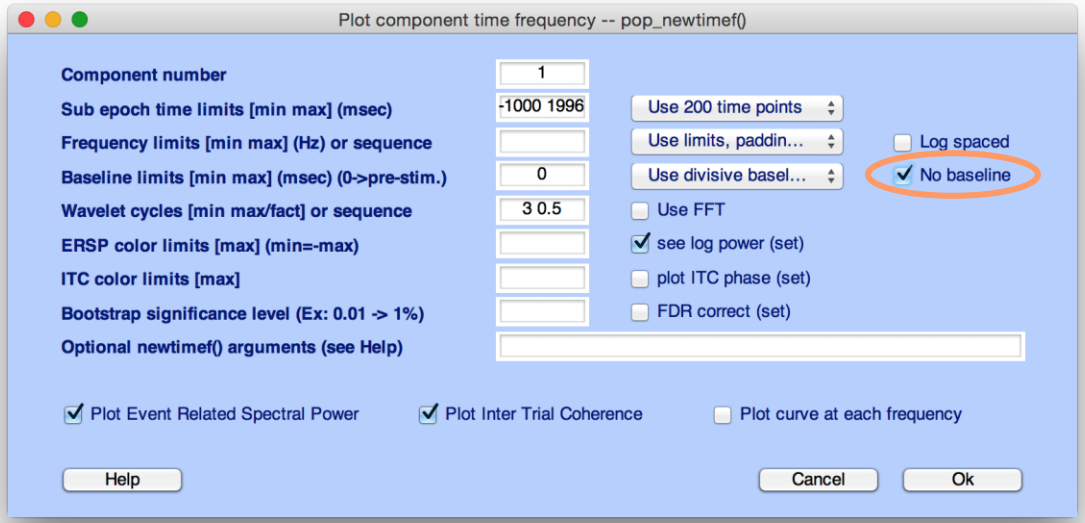


(Load faces_4.set

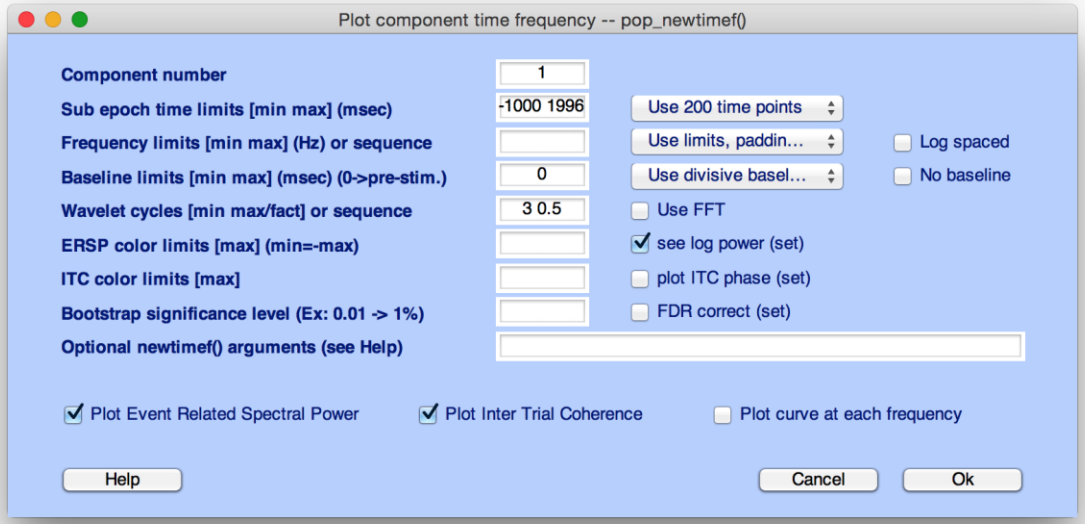
Epoch on 'face' event)

Display ERS vs. ERSP

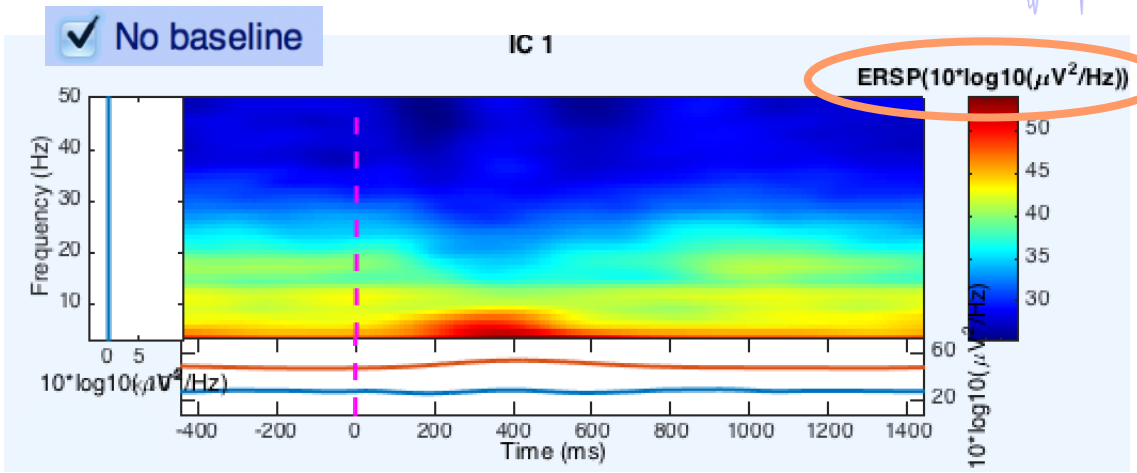
Event-related Spectrogram



Event-Related Spectral Perturbation (ERSP)

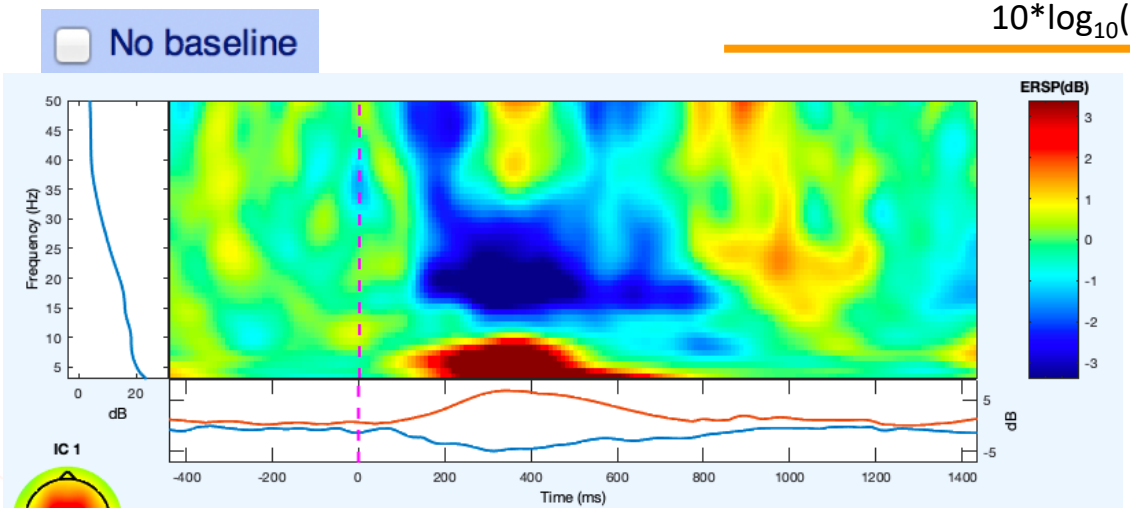


Event-related Spectrogram SG(t,f)



$10*\log_{10}(SG(t,f) \mathbf{/ baseline(f)})$

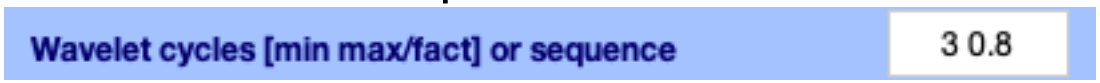
Event-Related Spectral **Perturbation** (ERSP)



$10*\log_{10}(SG(t,f)) - 10*\log_{10}(baseline(f))$

Exercises

- Try different wavelet specifications



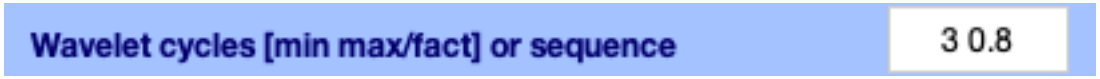
  - Default: 3 0.8
    - 3 cycles. Try 2. How do the time limits of the plot change?
    - What is the 0.8? Try 0. Try 1…what do you observe?

- Try different low-frequency limit

  - what is the effect on the time limits of the ERSP?

- Try different baseline methods
  - divisive
  - standard deviation (express spectral perturbations in #sd relative to baseline sd)

Wavelet Specification



Answer: The first #cycles controls the basic duration of the wavelet in cycles.

The second factor controls the degree of shortening of time windows as frequency increases

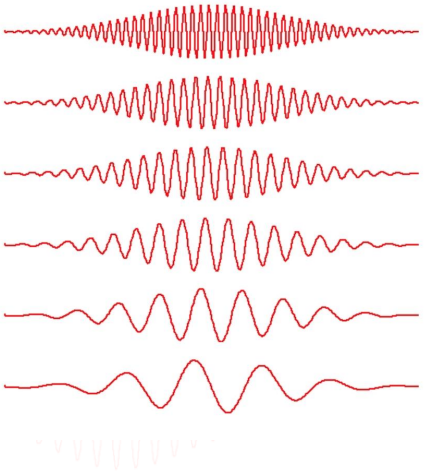
0 = no shortening = FFT (duration remains constant with frequency)

1 = pure wavelet (#cycles remains constant with frequency)

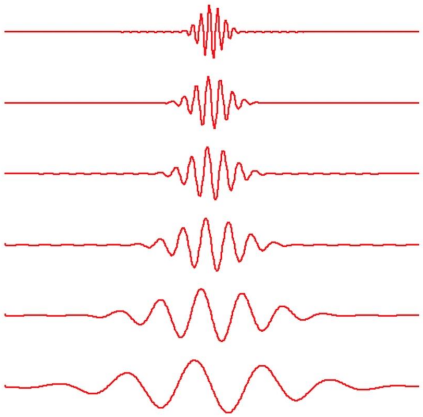
0.5 = intermediate, a compromise that reduces HF time resolution to gain more frequency resolution.

0.8 = EEGLAB default—higher HF time resolution

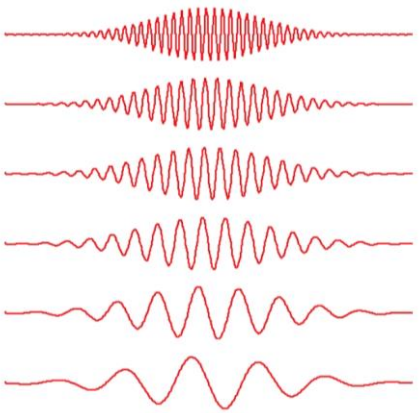
3 0



3 1

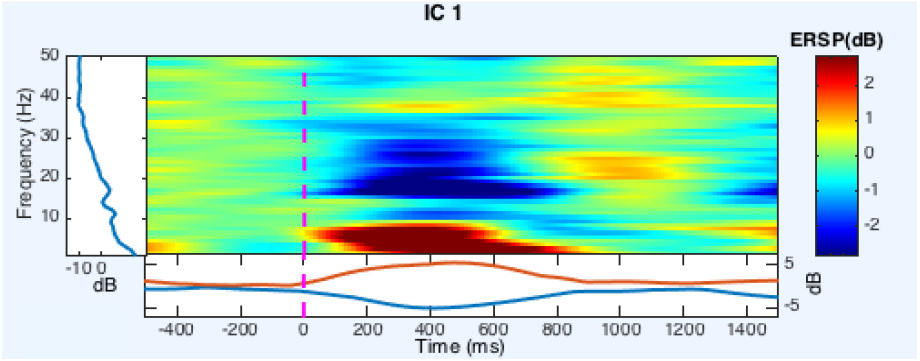


3 0.5

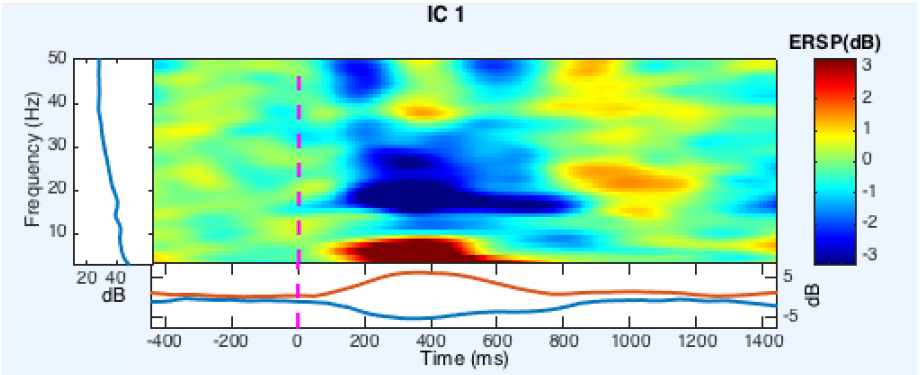


Comparison of FFT & Wavelet

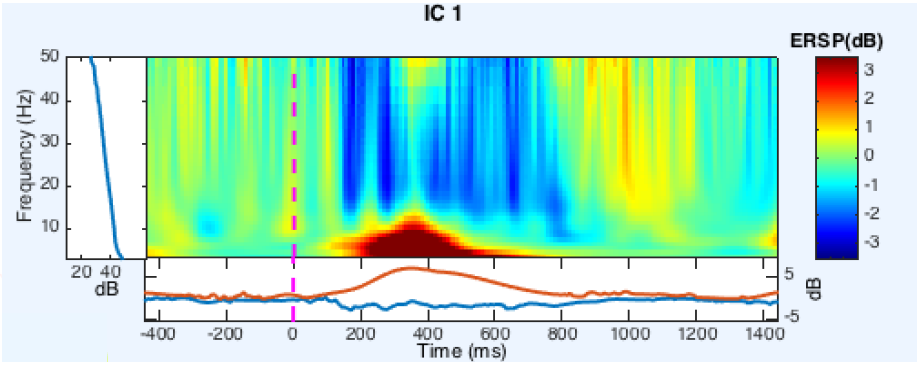
[3 0] (FFT)



[3 0.5] Wavelet



[3 1] Wavelet



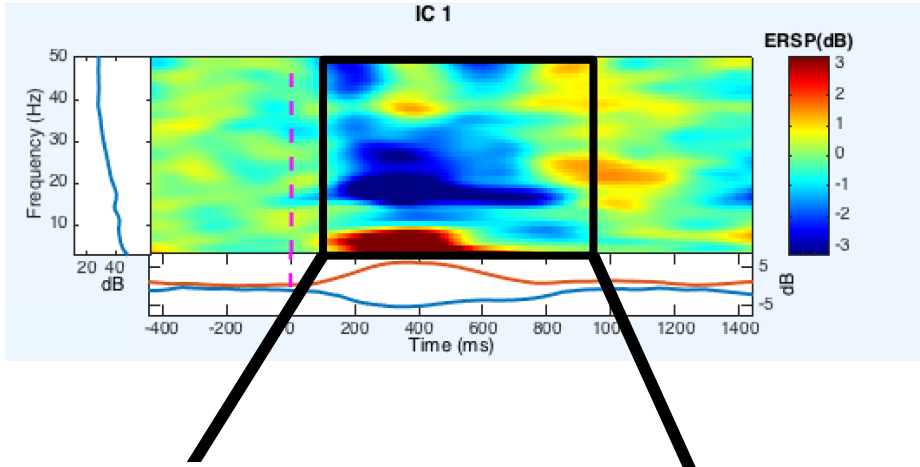
A reasonable choice:

Notice: features have similar time and frequency resolution

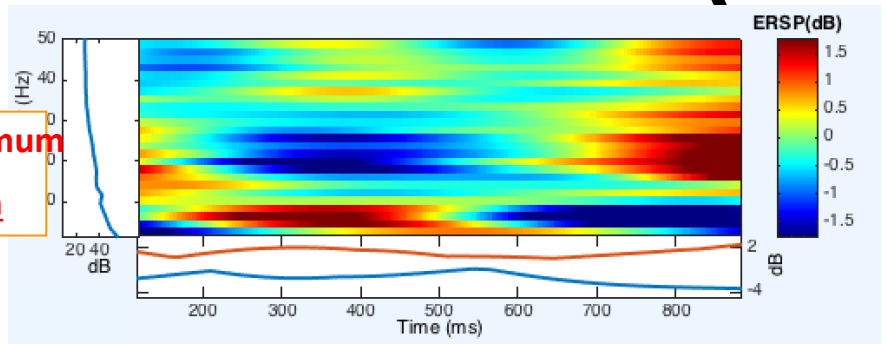
Time loss at edge of ERSP

- Settings for 1) *wavelet cycles* and 2) *lowest frequency* impact the time limits of analysis

MIN FREQ: 3 Hz



MIN FREQ: 1 Hz



***more wavelet cycles, or a lower minimum frequency loses time at edges of epoch**

Solution: If you need low frequencies in your ERSP, be sure to extract longer epochs to counteract this. If you can't re-epoch, then try reducing the number of wavelet cycles.

Part 3: Coherence Analysis

- Goal: How much do two signals resemble each other?

- Coherence = complex version of correlation: how similar are power and phase at each frequency?

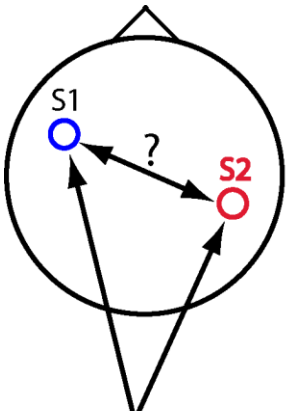
- Variant: phase coherence (phase locking, etc.) considers only phase similarity, ignoring power
  - Regular coherence is simply a power-weighted phase coherence
  - Inter-trial coherence is useful!

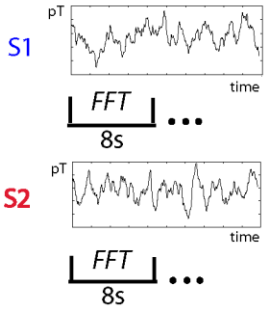
- NOTE: For **understanding** connectivity between regions, *channel* coherence is a poor choice due to volume conduction. For IC connectivity, directional, 'causal' measures of connectivity have been developed (See SIFT lecture).

Coherence

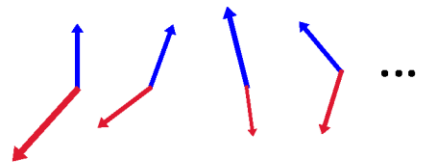
$$C(f,t) \mu \sum_{k=trials} F1_k(f,t)\overline{F2_k(f,t)}$$

$$a_1 e^{iq_1} a_2 e^{-iq_2} \mu e^{i(q_1 - q_2)}$$

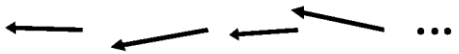


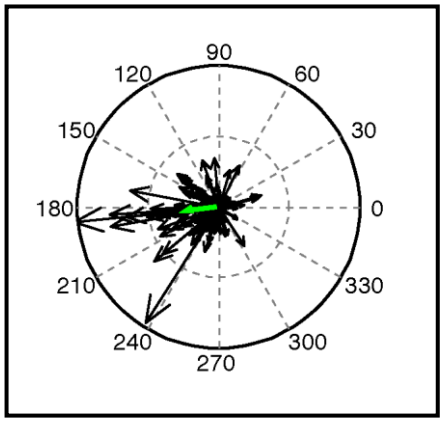


Fourier time series F_{S1} and F_{S2}



Phase difference between S1 and S2,

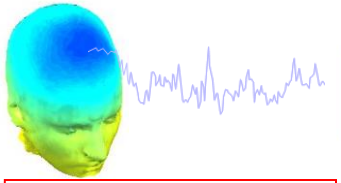




Part 3a: Inter-Trial Coherence

- Goal: How much do different trials resemble each other?
- Phase coherence not between two processes, but between multiple trials of the same process
- Defined over a (generally) narrow frequency range

ITC Example (3 trials)



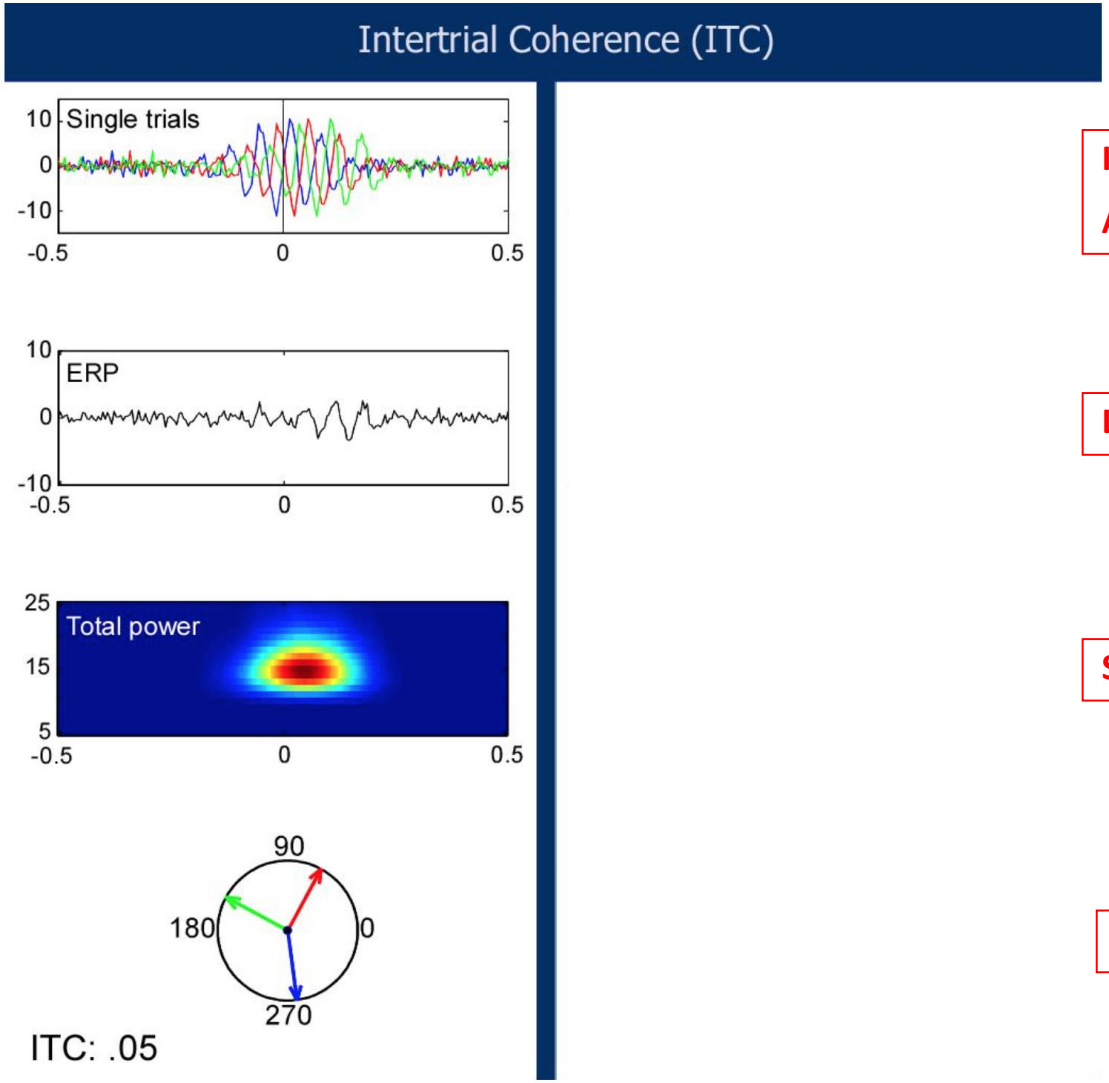
Increased power,

no phase alignment

small ERP

'Induced' power

Low ITC



Increased power,

AND phase alignment

Large ERP

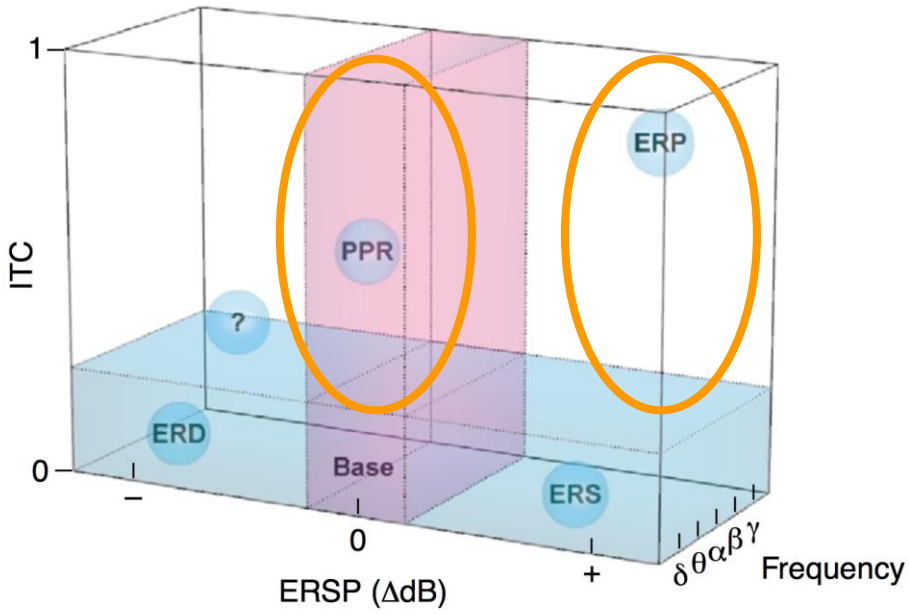
Same power

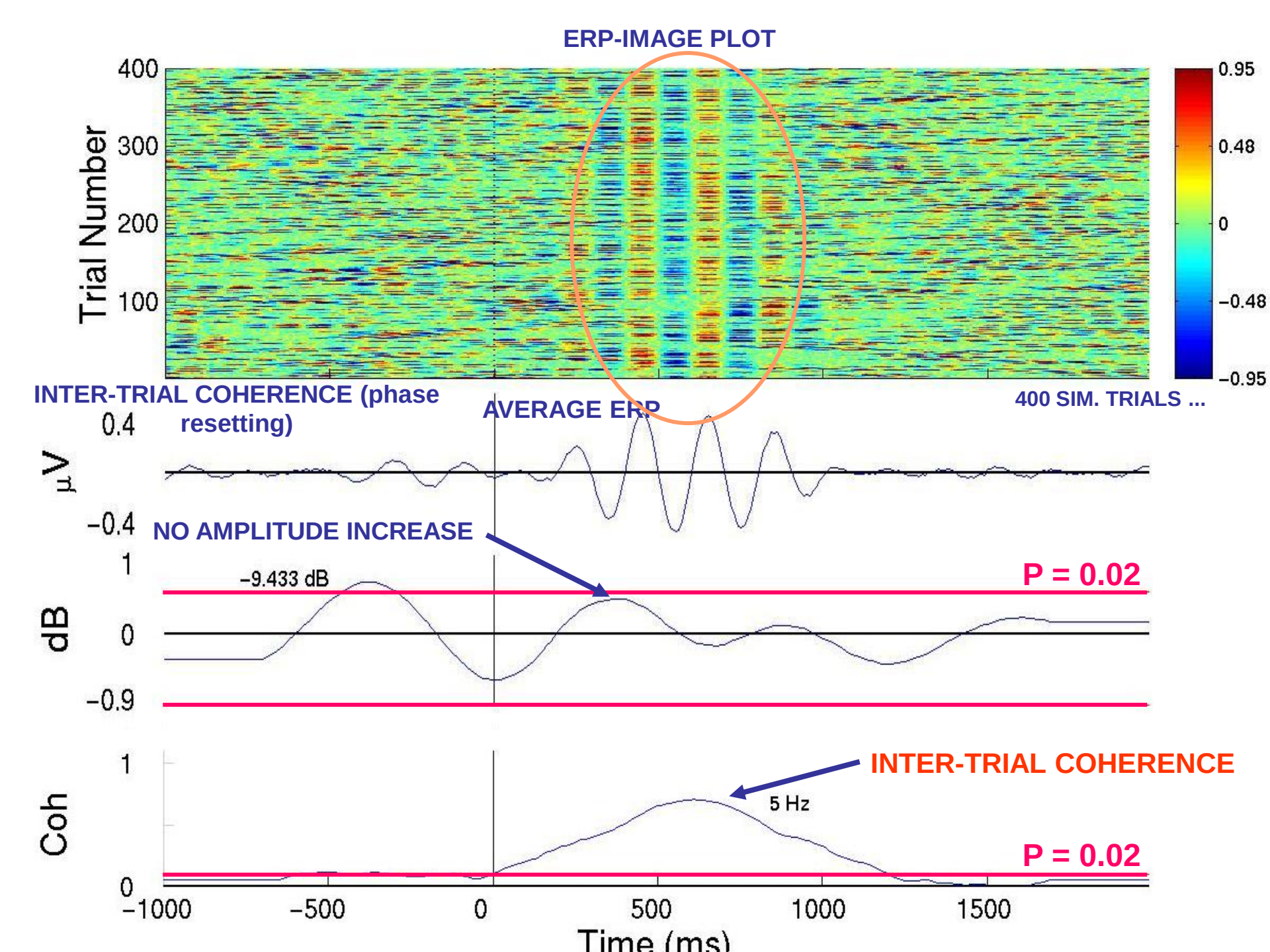
High ITC

Slide courtesy of Stefan Debener

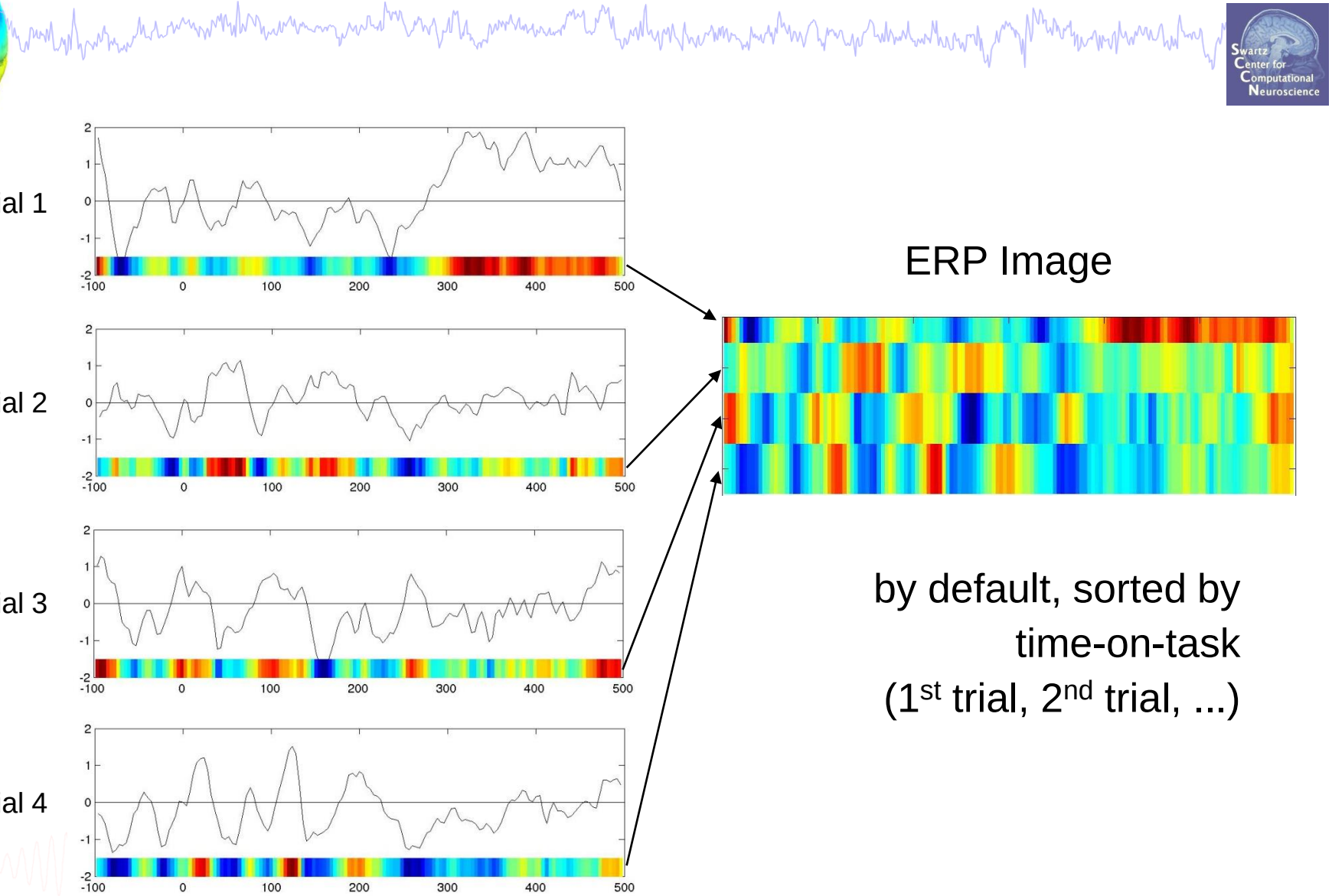
** Several possible origins of an ERP **

- Event Related Potential can result from
  - ITC increase (with no change in power)
  - ITC & Power change

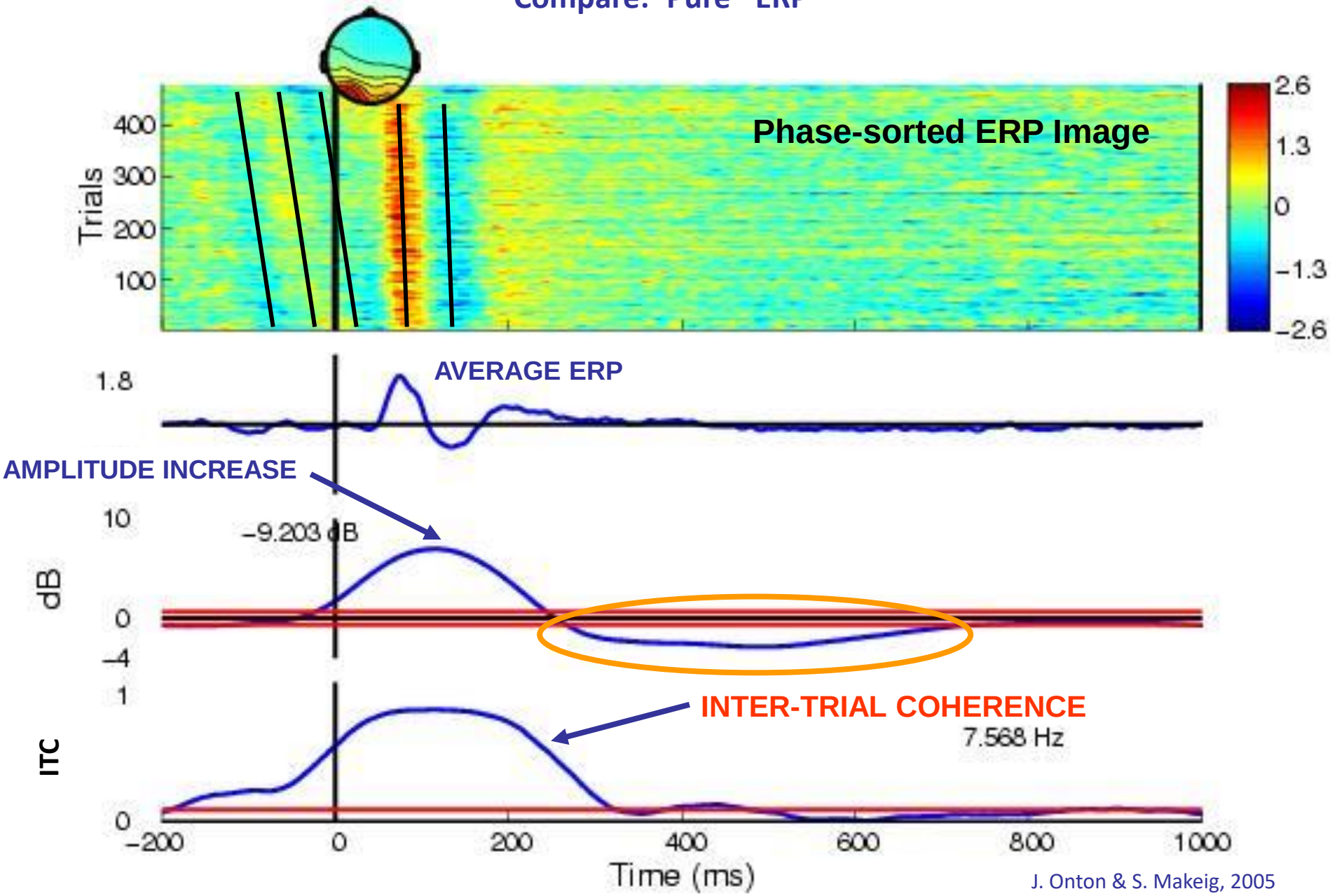



ERP-IMAGE PLOT
Trial Number
400
300
200
100
0.95
0.48
0
−0.48
−0.95
INTER-TRIAL COHERENCE (phase resetting)
AVERAGE ERP
400 SIM. TRIALS ...
μV
0.4
−0.4
NO AMPLITUDE INCREASE
dB
1
0
−0.9
−9.433 dB
P = 0.02
Coh
1
0
5 Hz
INTER-TRIAL COHERENCE
P = 0.02
−1000
−500
0
500
1000
1500
Time (ms)

(ERP Image basics → Johanna Wagner [Wednesday AM])

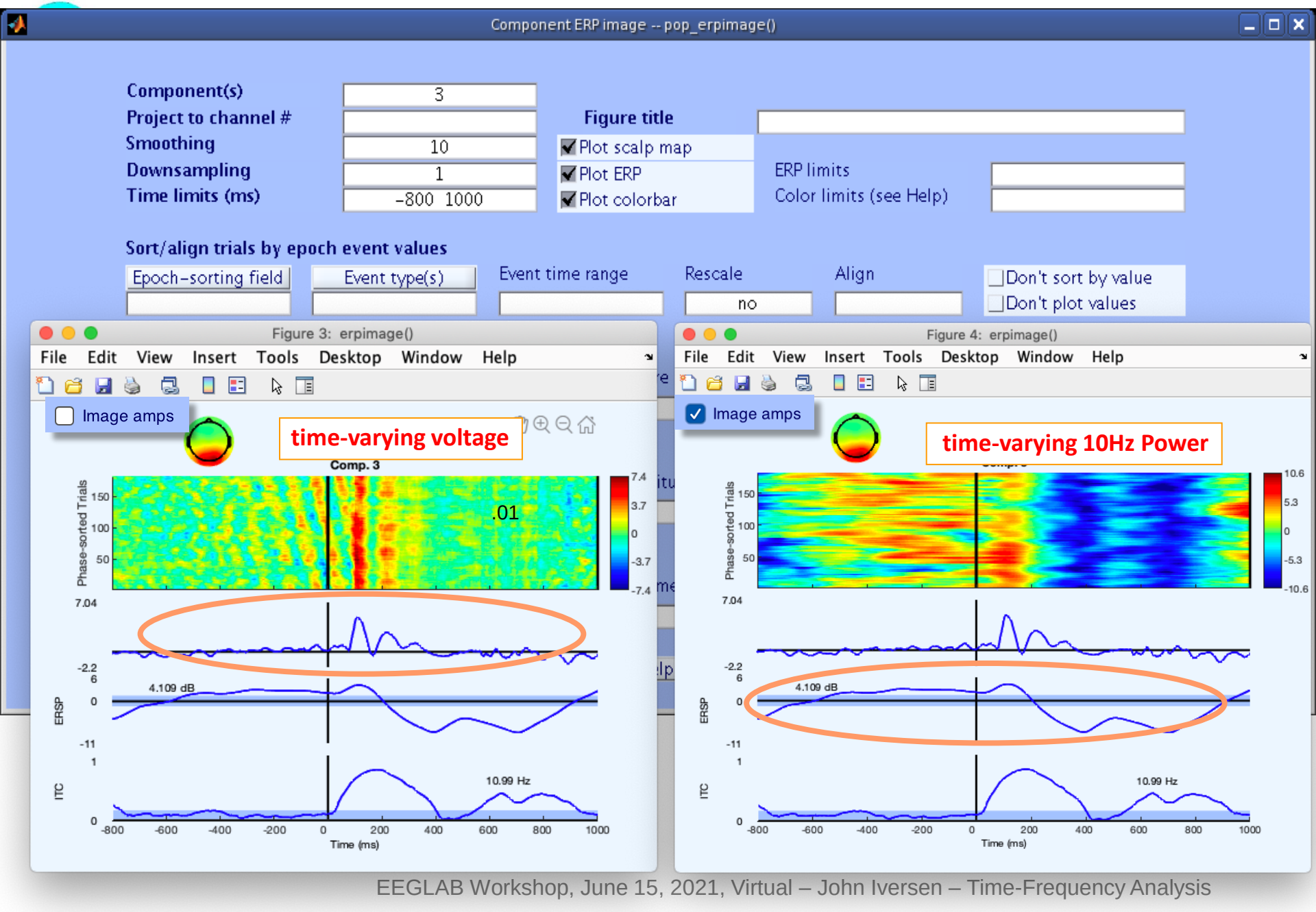


Compare: 'Pure' ERP

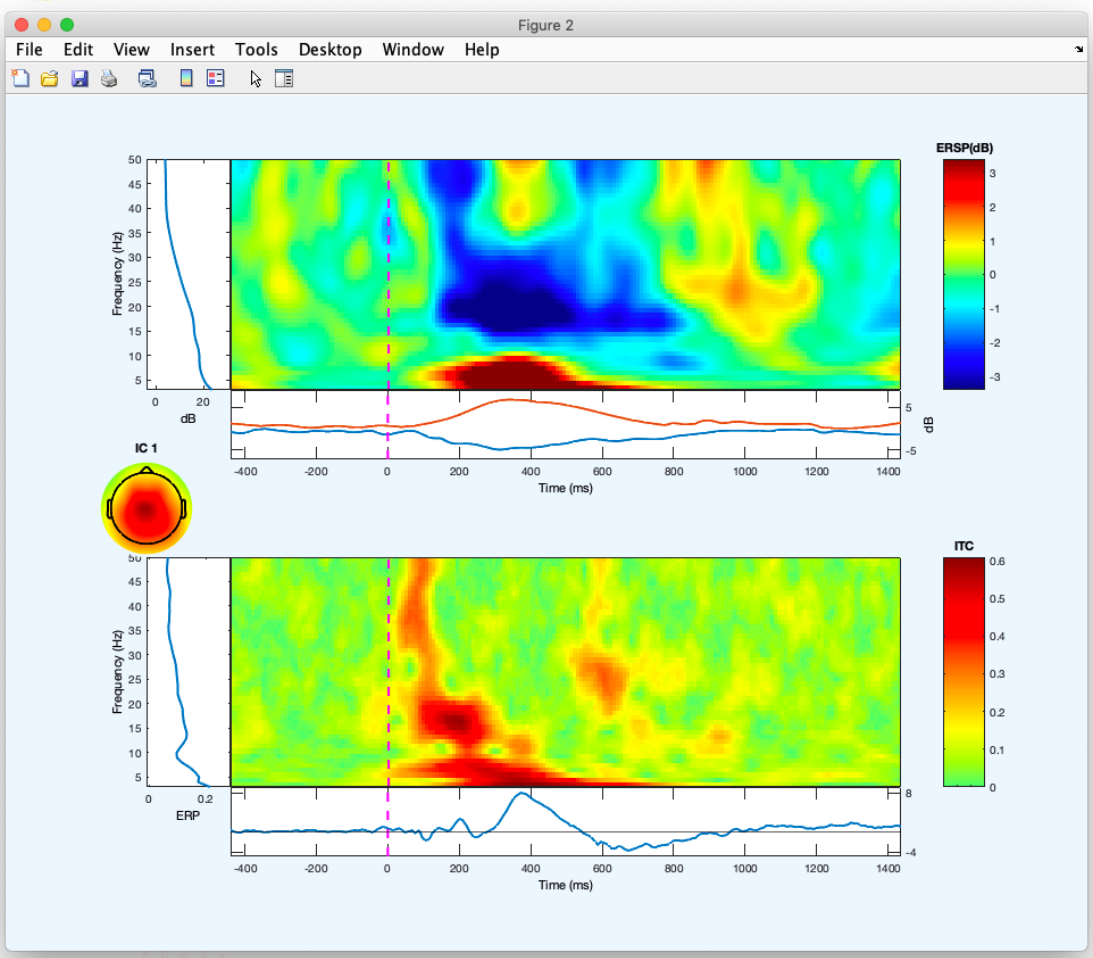


J. Onton & S. Makeig, 2005

Component ERP Image: Activation vs. Amplitude



Putting it all together



Exercise

All: Compute ERSP/ITC for a component of your choice

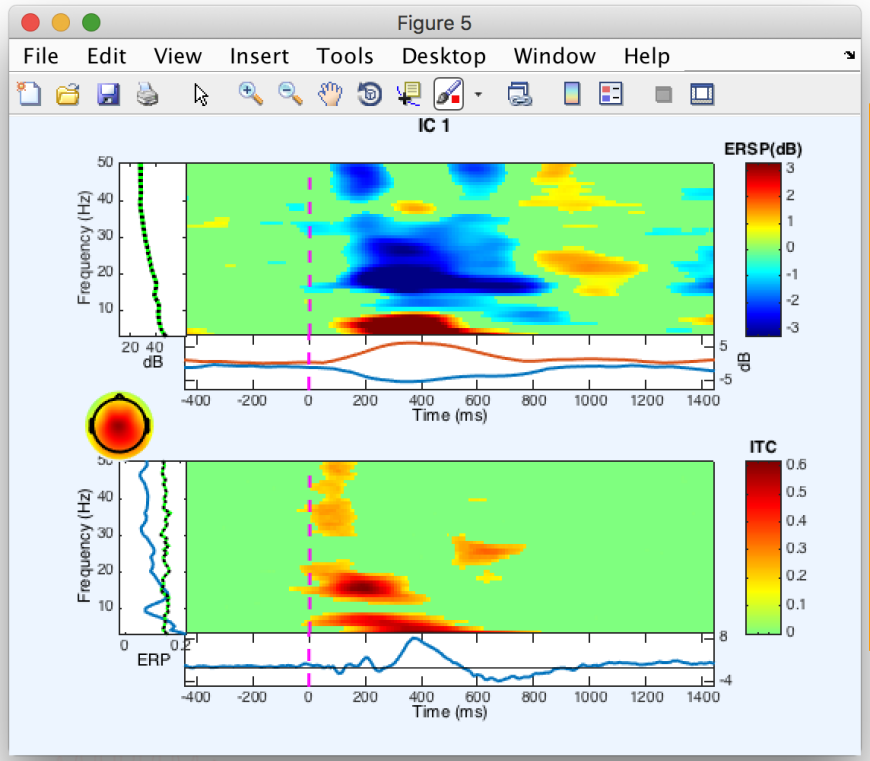
Compute ERP Image (with ERSP and ITC displayed*)

Use all of this information to explain the origin of the Evoked Response

Question: Which changes are significant? Use the options in ERP Image and ERSP dialogs to set significance threshold e.g. 0.01. Do the results survive?

Significance Testing

- Keep in mind: "is this significant?"



Method: Bootstrap

Green areas are not significant.

Scale of ERSP & ITC vales also give a clue:

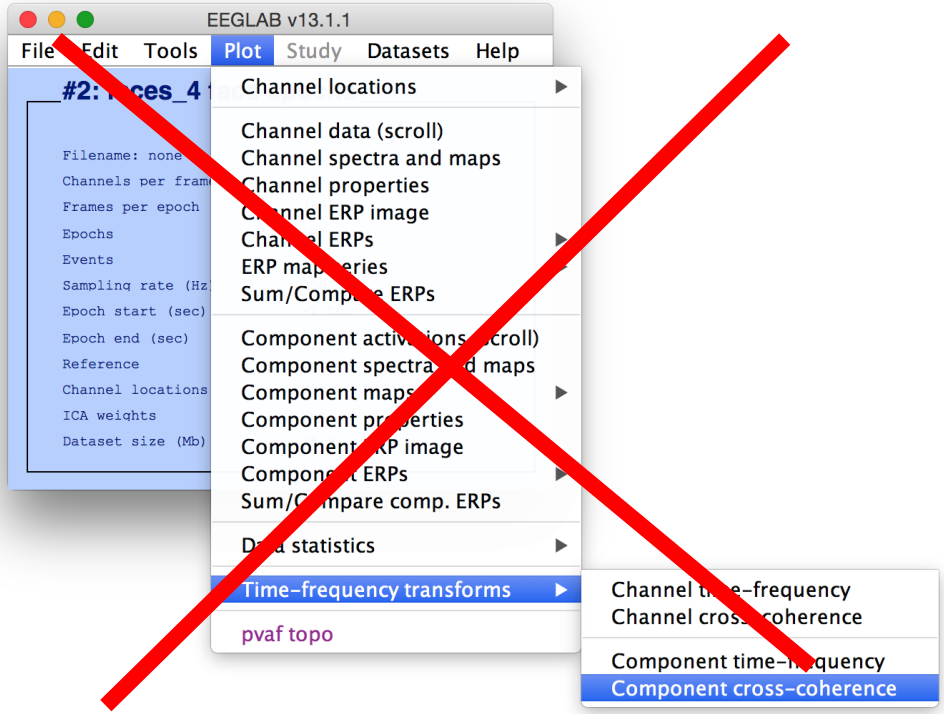
Large values are often encouraging of a significant effect

(Large ≈ > 1dB for ERSP; > 0.5 for ITC)

For exploratory purposes, can try 0.01 without FDR correction

Bonus: Part 3b: Event Related Coherence

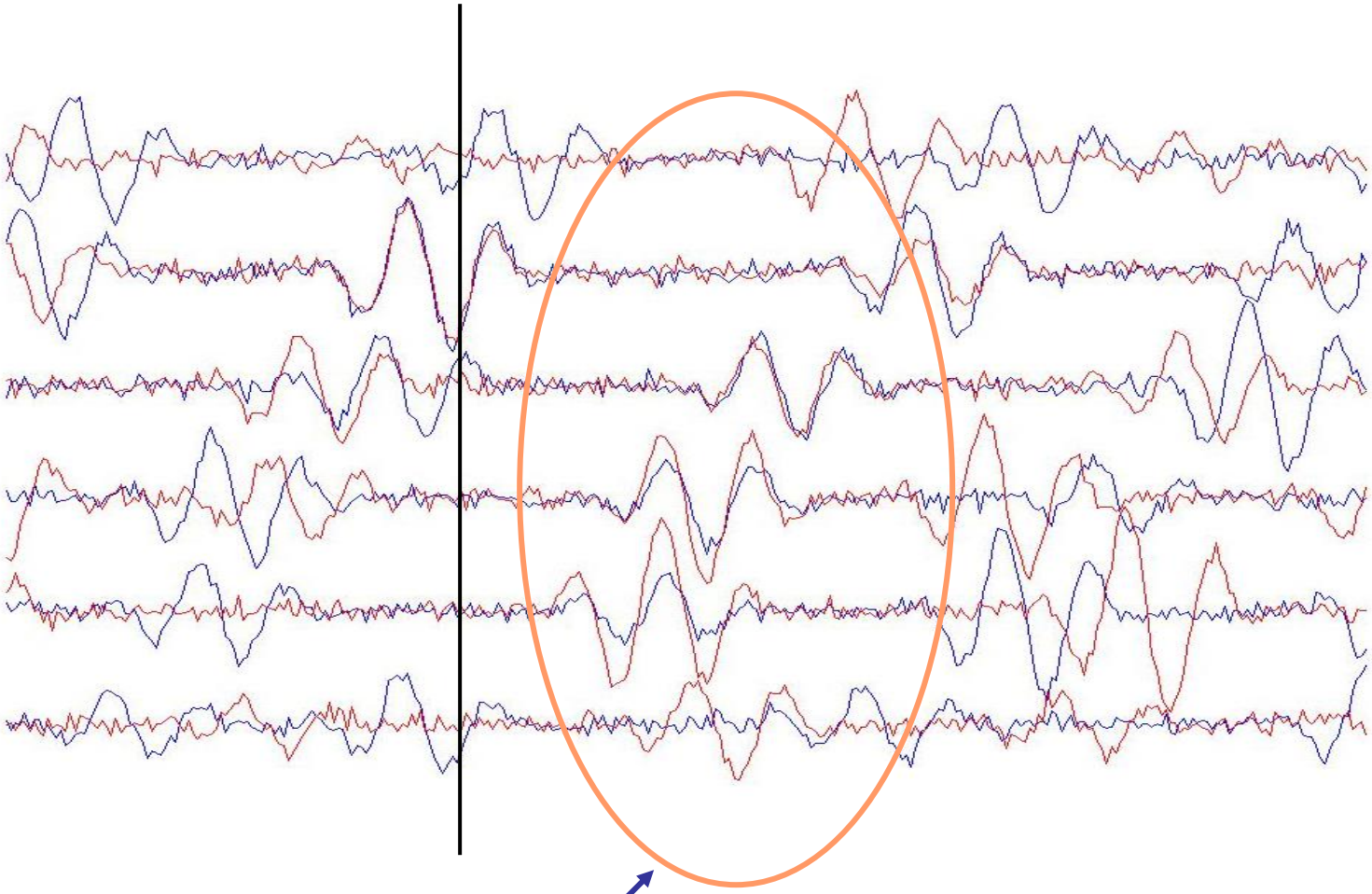
- Goal: How similar is the event-related response of two signals?
  - Between channels (problematic due to volume conduction)
  - Between ICs
  - Useful to quickly begin to understand relationships between components
  - SIFT provides more complete solution



No longer accessible through GUI

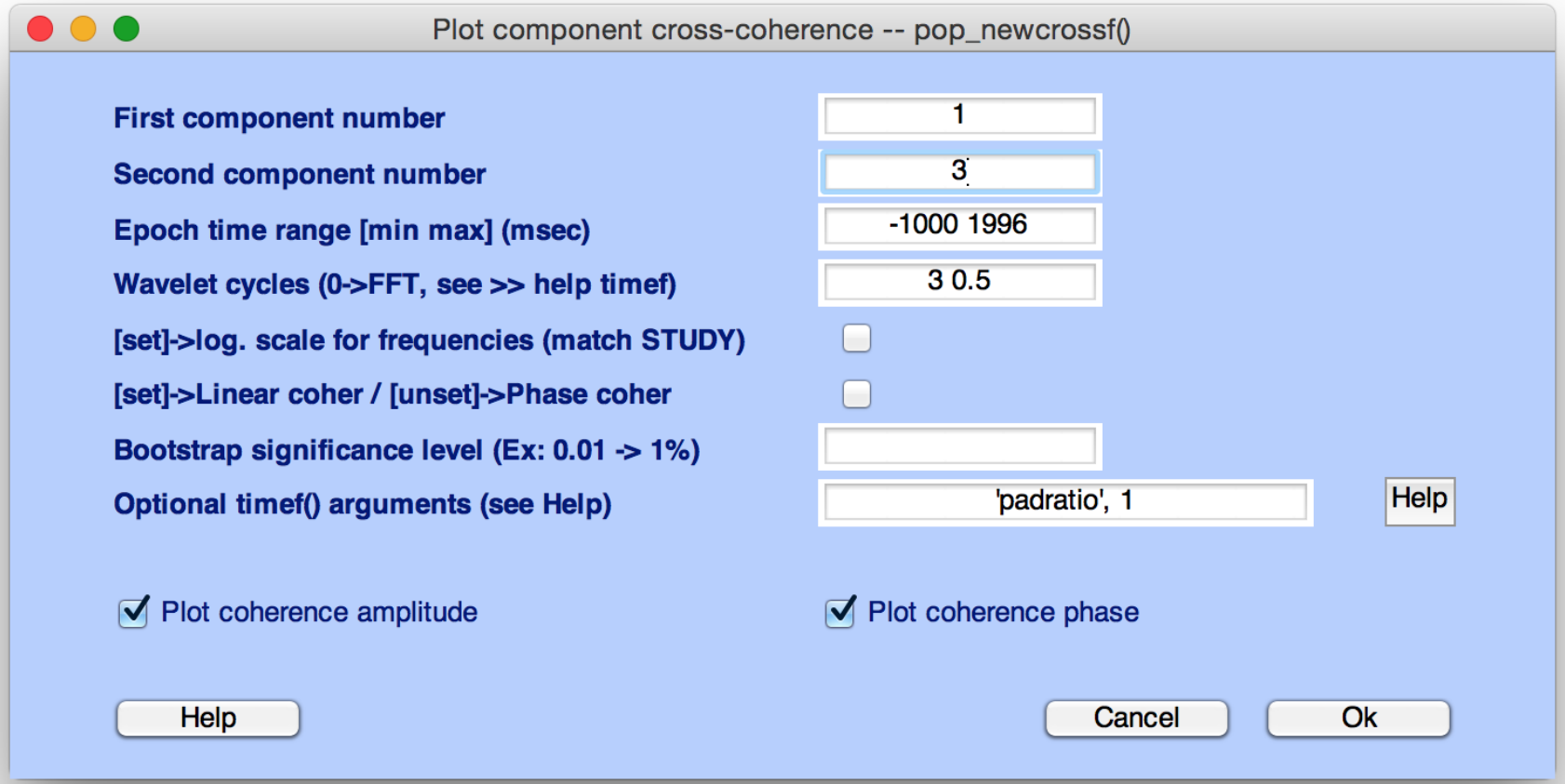
pop_newcrossf(EEG, 0);

TWO SIMULATED THETA PROCESSES



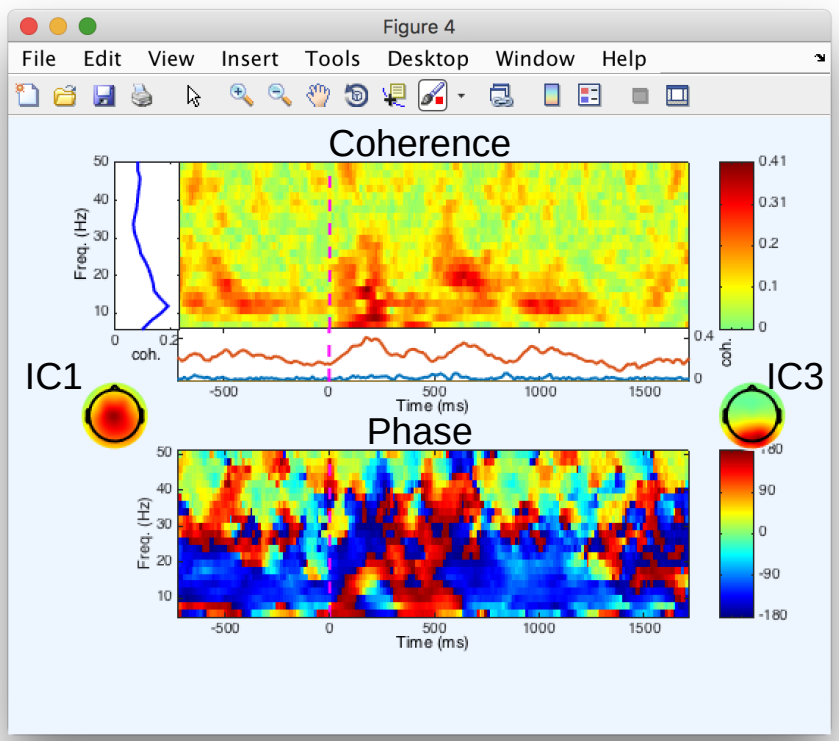
Event-related Coherence

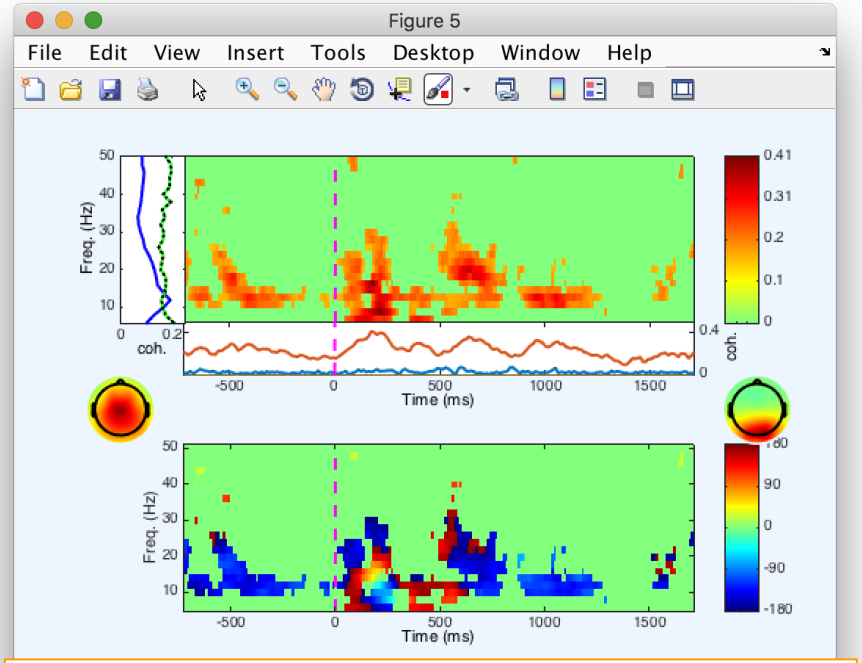
Try it!


Plot component cross-coherence -- pop_newcrossf()
First component number
1
Second component number
3
Epoch time range [min max] (msec)
-1000 1996
Wavelet cycles (0->FFT, see >> help timef)
3 0.5
[set]->log. scale for frequencies (match STUDY)
[set]->Linear coher / [unset]->Phase coher
Bootstrap significance level (Ex: 0.01 -> 1%)
Optional timef() arguments (see Help)
'padratio', 1
Help
Plot coherence amplitude
Plot coherence phase
Help
Cancel
Ok

Cross coherence between IC 1 and IC 3

$\alpha = 0.01$





Significant event-related coherence (as well as tonic coherence) in alpha/beta bands

IC 1 tonically leads IC 3 (negative phase), but phase relationships are changed post-stimulus

More advanced, directional, measures of effective connectivity *are present in the SIFT toolbox (a later lecture).*

Event-Related Coherence Exercise

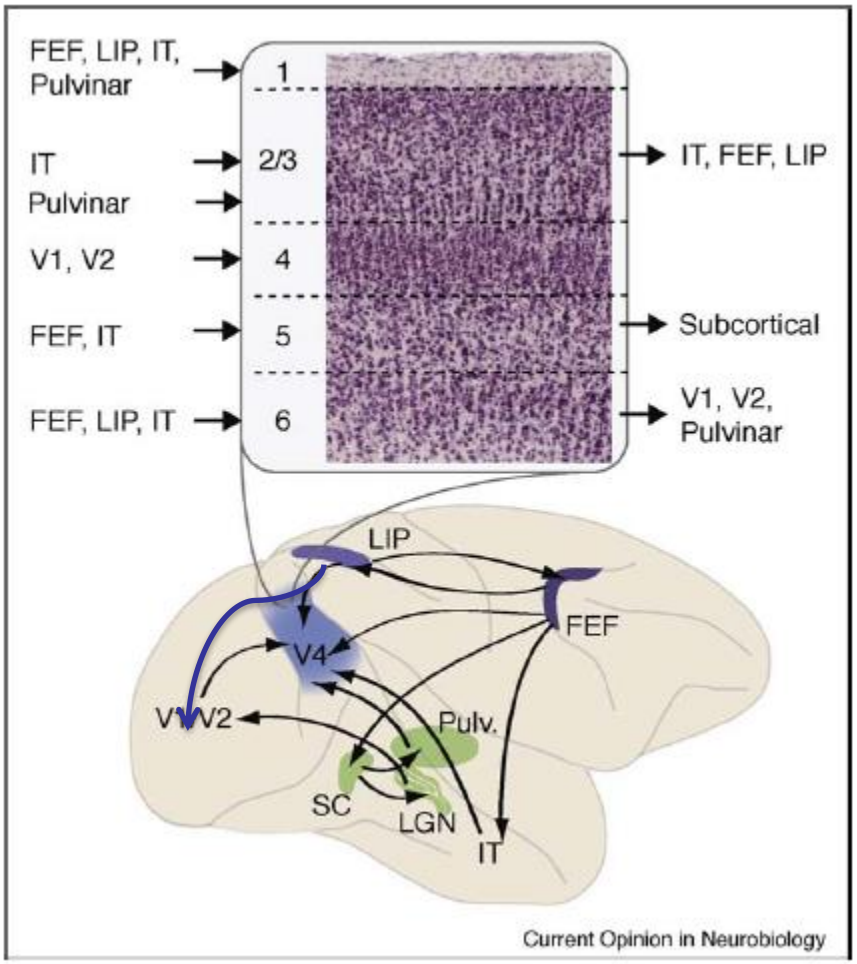
- Examine event-related coherence between two ICs
  - Which pair did you pick, and why? What do you predict?
  - What did you learn?

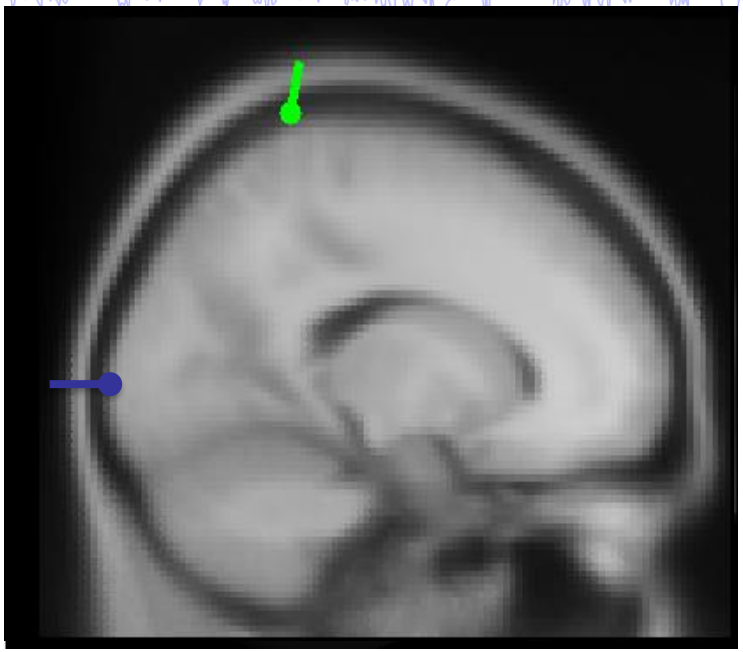
- Explore other options:
  - Significance threshold
  - Figure out how to subtract a baseline
  - Phase vs. Linear Coherence

Part 4: Other Applications

- Information Flow: Autoregressive modeling → time/frequency resolved directed information flow
  - **SIFT** – Tim Mullen [Tomorrow, Connectivity Analysis Track]
- Cross-frequency Analysis
  - **Phase/amplitude coupling (PAC) -** Ramón Martinez-Cancino [Right after this talk!]

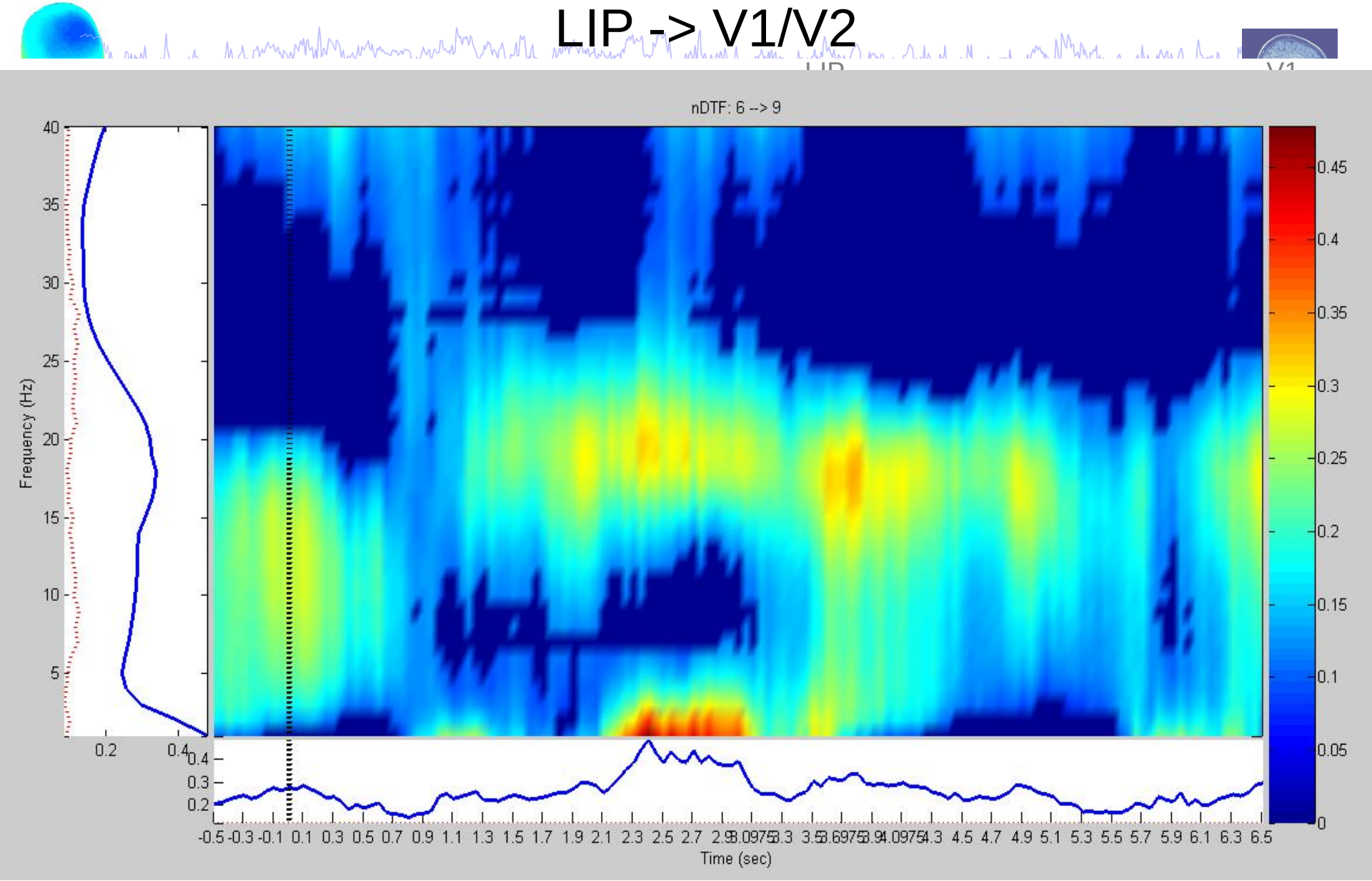
Aktualne badania



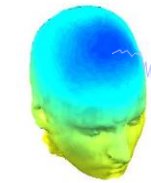


Aktualne badania: matoda

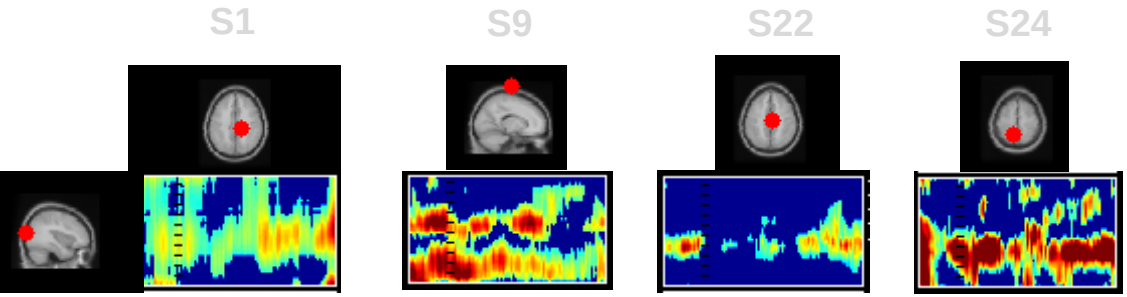
LIP -> V1/V2



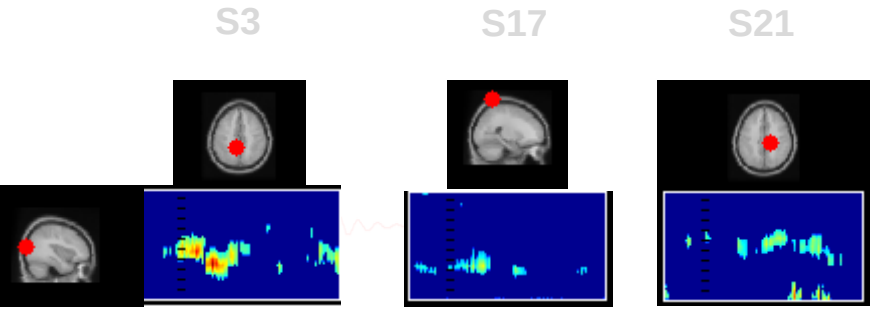
Young



EHP



ELP



PRACTICUM

- Follow the red bordered slides, using the faces_4.set, epoched on the 'face' event.