ILCB Institute of Language, Communication and the Brain

Summer school

Hitch-hiker's Guide to the Galaxy...

of

EEG

Engineering Techniques. Thursday 2nd September 2021

2021 Summer School of the Institute of Language, Communication and the Brain

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"This must be Thursday," said Arthur to himself, sinking low over his beer. "I never could get the hang of Thursdays."

- Douglas Adams,
The Hitchhiker's Guide to the Galaxy

The CREx Team

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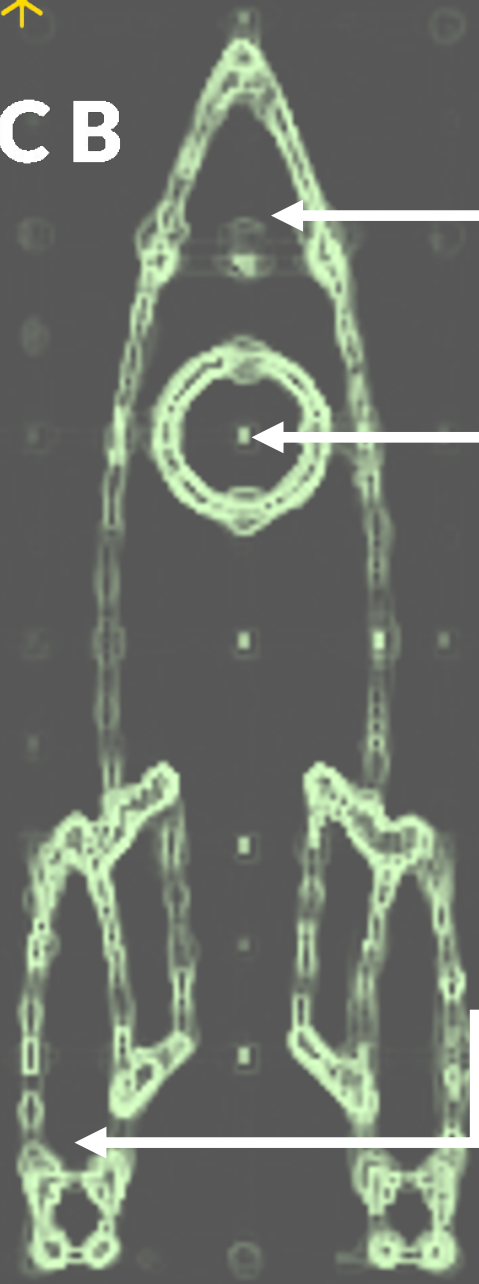

Part 1: Brain Oscillations – Very quick Introduction

Part 2: Analyzing Brain Oscillations in EEG

Part 3: Brain Oscillations in BCI – Live Demonstrations

Brain Oscillations

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Same input ➔ same response.

Same input ➔ same response?

Spontaneous or « endogenous » oscillatory activity

The complex pattern of neural activity generated « spontaneously » by the brain even in the absence of sensory input or task execution.

Brain Oscillations: In the beginning

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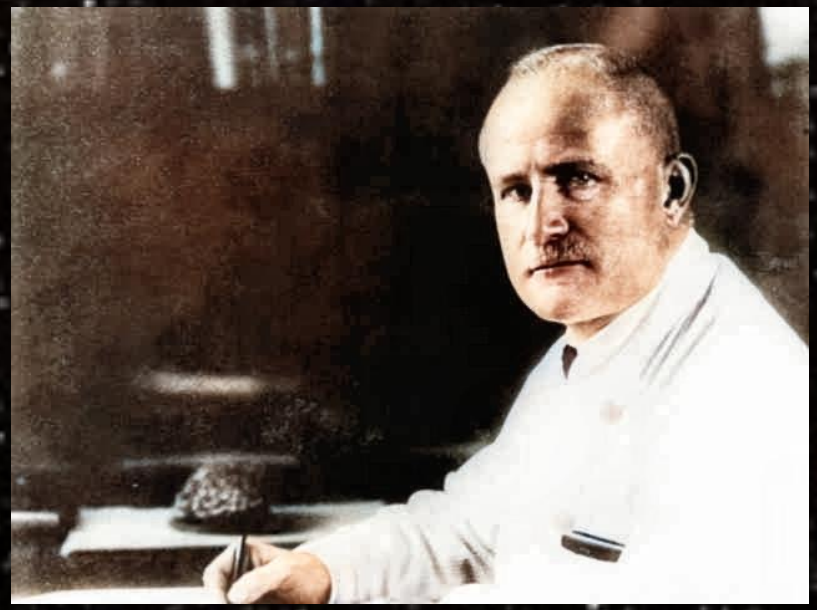
Richard Caton
1873 - 1941

First ever EEG (1874)

Adolf Beck 1863 - 1942

First to describe desynchronization in electrical waves after stimulation.

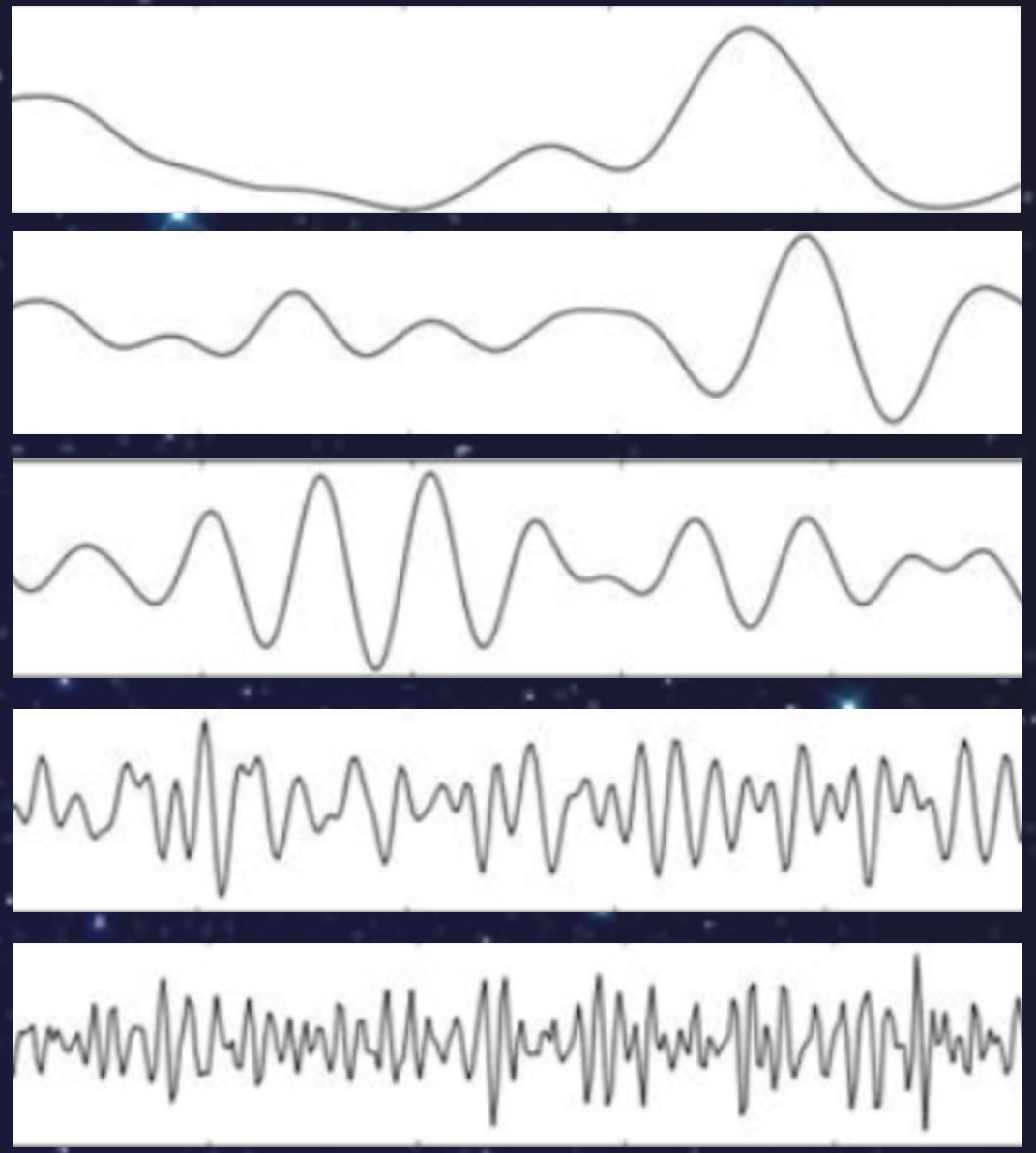
Hans Berger 1873 - 1941



First ever recording of human EEG (1924)

Taxonomy of Brain Oscillators in EEG

- Delta (δ): 0.5 – 4Hz
- Theta (θ): 4 – 8Hz
- Alpha (α): 8 – 12Hz
- Beta (β): 12 – 30Hz
- Gamma (γ): > 30Hz



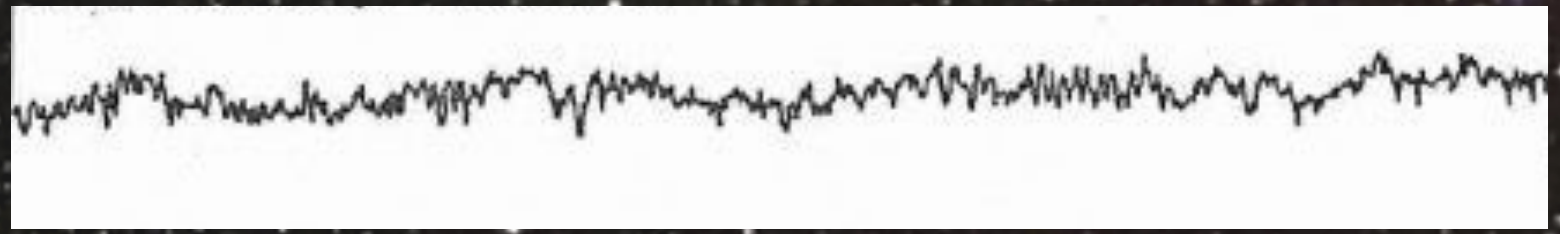
Brain Oscillations: In the beginning…

« Adrian and Matthews recently gave an elegant demonstration of these cortical potentials. […] when the subject's eyes were open the line was irregular, but when his eyes were shut, it showed a regular series of large waves occurring about ten a second. […] then came the surprise. When the subject shut his eyes and was given a simple problem in mental arithmetic, as long as he was working it out the waves were absent and the line was irregular, as when his eyes were open. When he has solved the problem, the waves reappeared. […] so, with this technique, thought would seem to be a negative sort of thing; a breaking of the synchronised activity of enormous numbers of cells into an individualized working ».

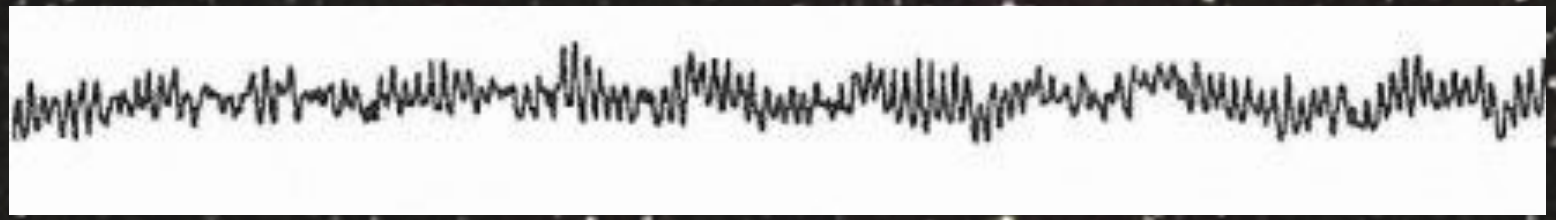
Report on a public demonstration in the British magazine, Spectator, (Walter, 1934, P. 479)

Brain Oscillations:

Bad By-Product or Functionally Relevant?



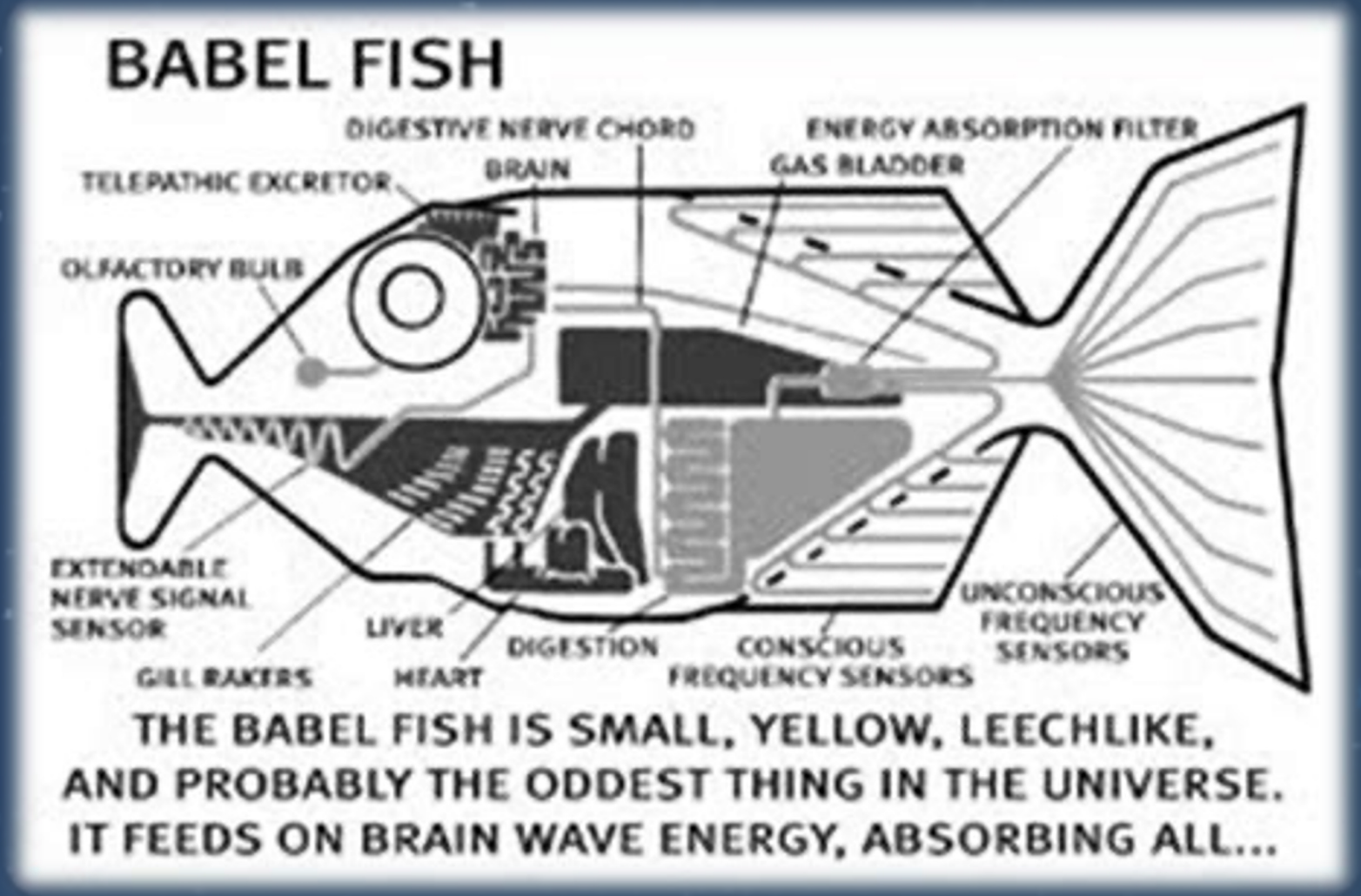
Waking EEG (β oscillations, 12-30Hz)



Drowsy/relaxed EEG (α oscillations, 8-12Hz)

Deep sleep EEG (δ oscillations, 0.5-4Hz)

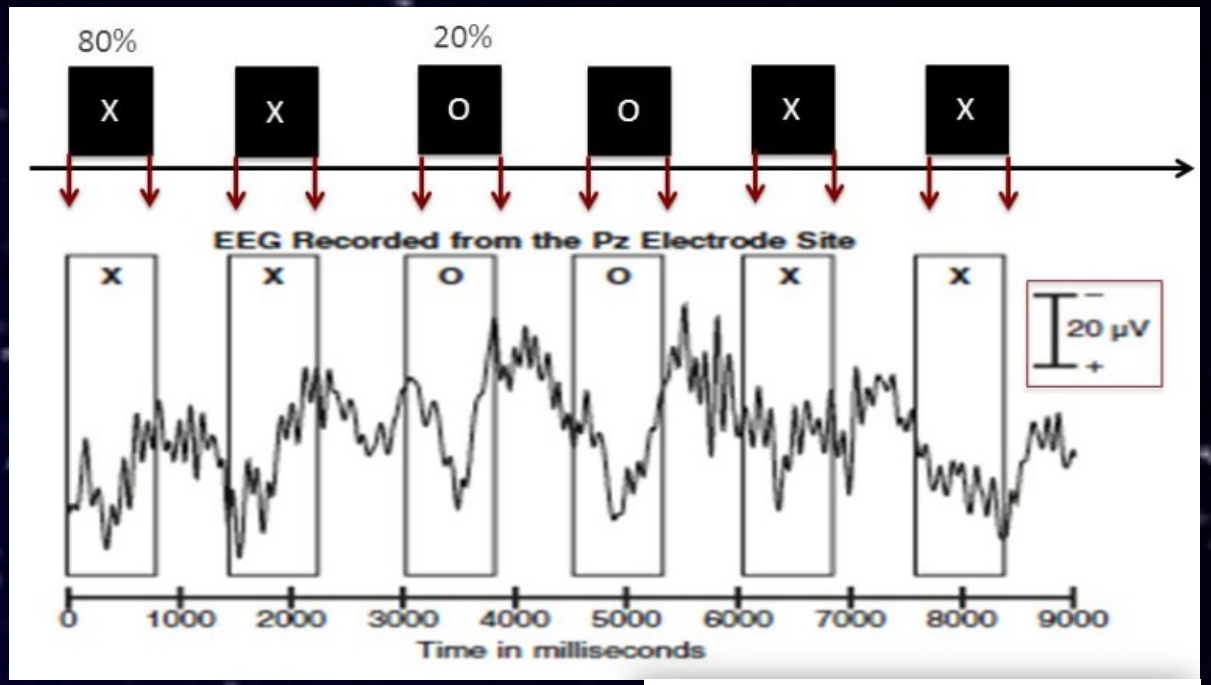
Brain Oscillations:
Only useful for the Babel fish?

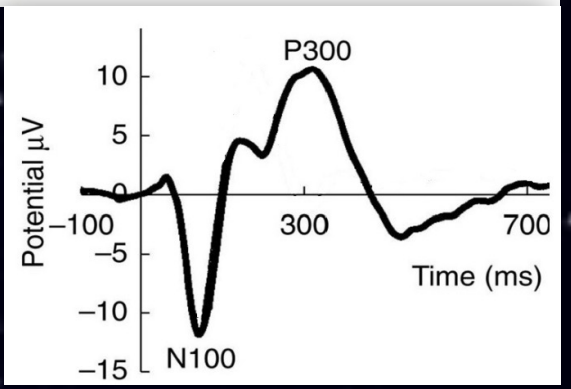


Brain Oscillations:
Implications for EEG Analysis

From 1960s, EEG research into human cognition dominated by the study of Event-Related Potentials (ERPs)

Assumption that a large part of the EEG signal is unrelated to brain responses related to the processing of experimental stimuli.





Brain Oscillations: Origins

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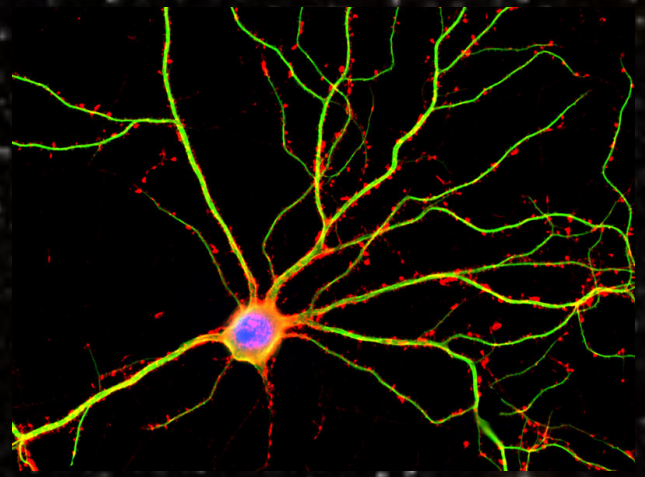
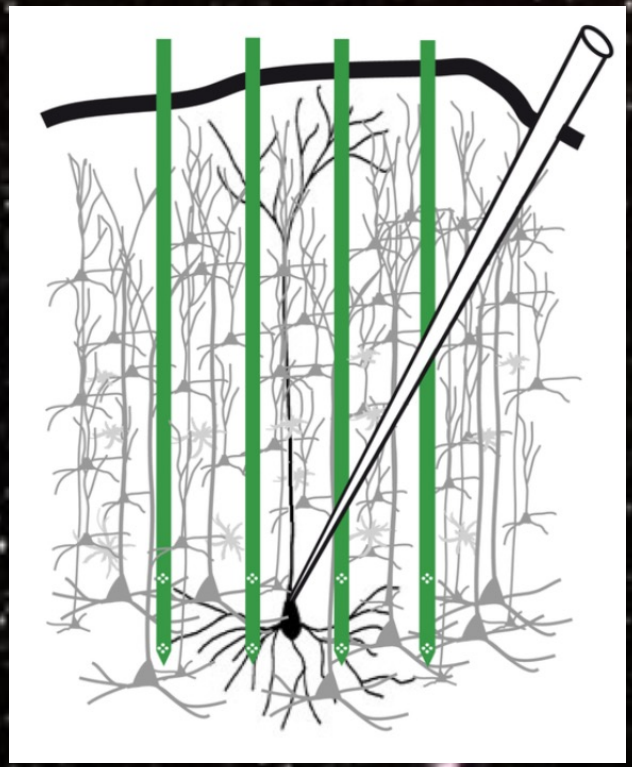
Rhythmic fluctuations in neural excitability measured at the level of:

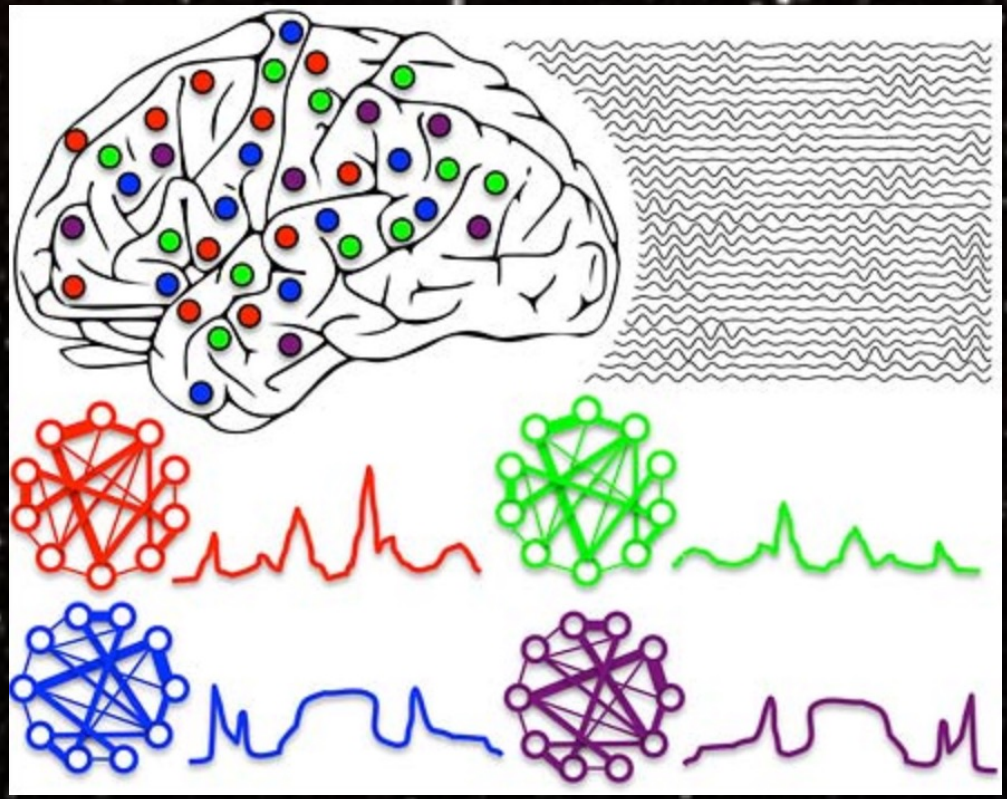
Individual Neurons



Local Neuronal Populations



Multiple distributed neuronal assemblies

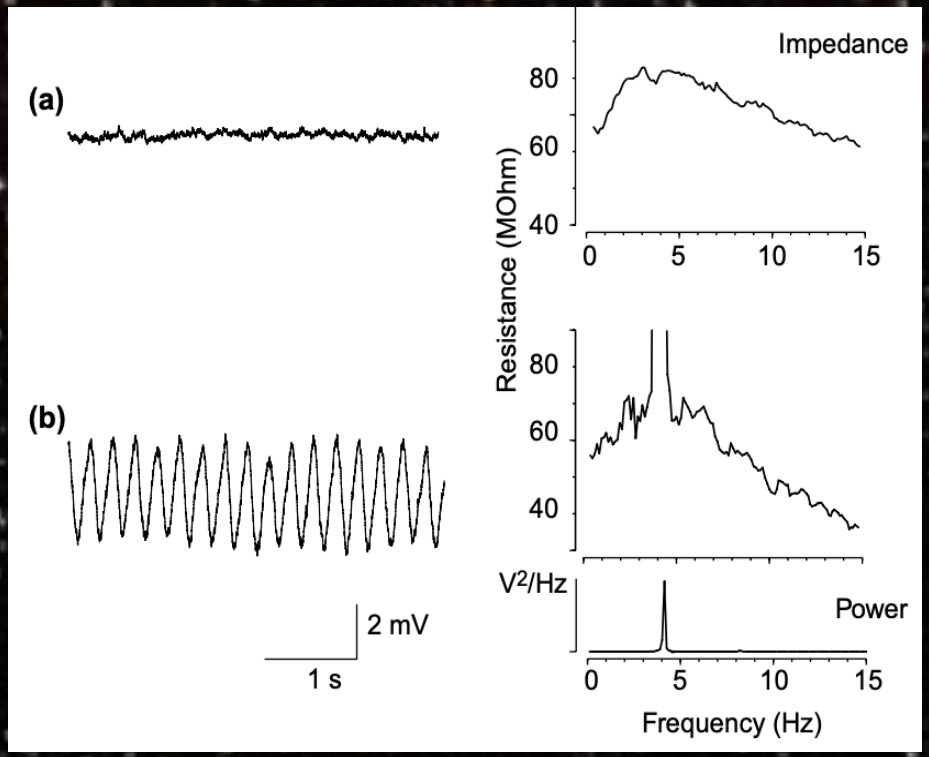


(Ryan Canolty, UC Berkeley)

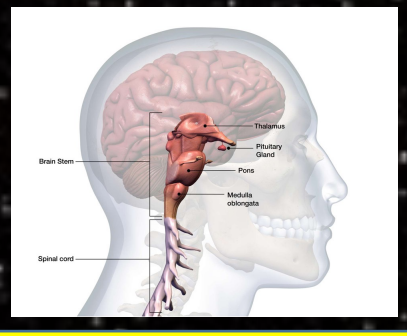
Brain Oscillations: Origins

Biophysical studies of single neurons have shown:

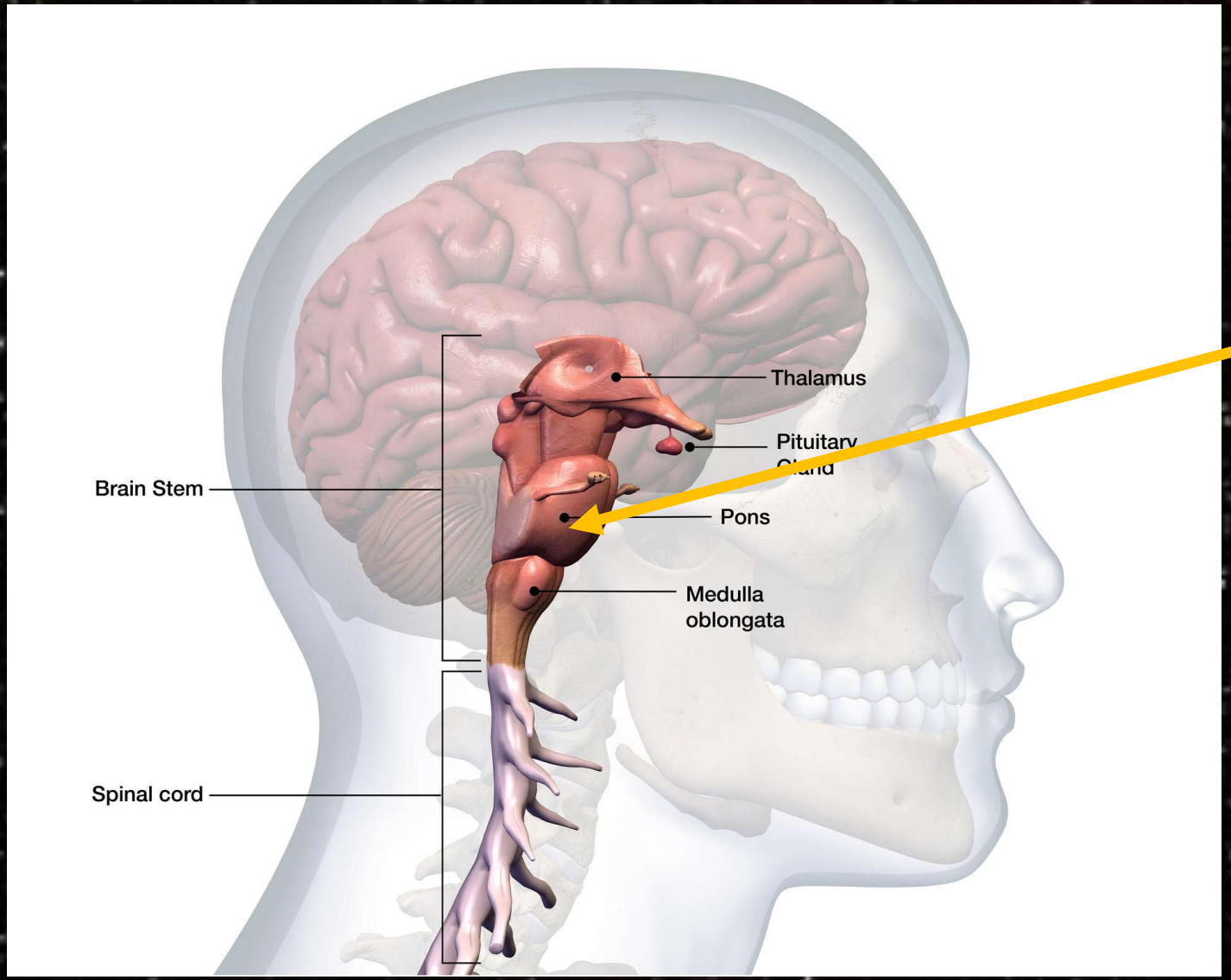
- Individual neurons can oscillate a different frequencies and generate spontaneous oscillations,
- Individual neurons can have frequency preferences,
- Individual neurons can respond best to or « resonate » within a certain narrow frequency window,



(Hutcheon & Yarom, Trends in Neuroscience, 23, 216, 2000)



Brain Oscillations: Origins



Superior
Olivary
Nucleus

Brain Oscillations: Origins

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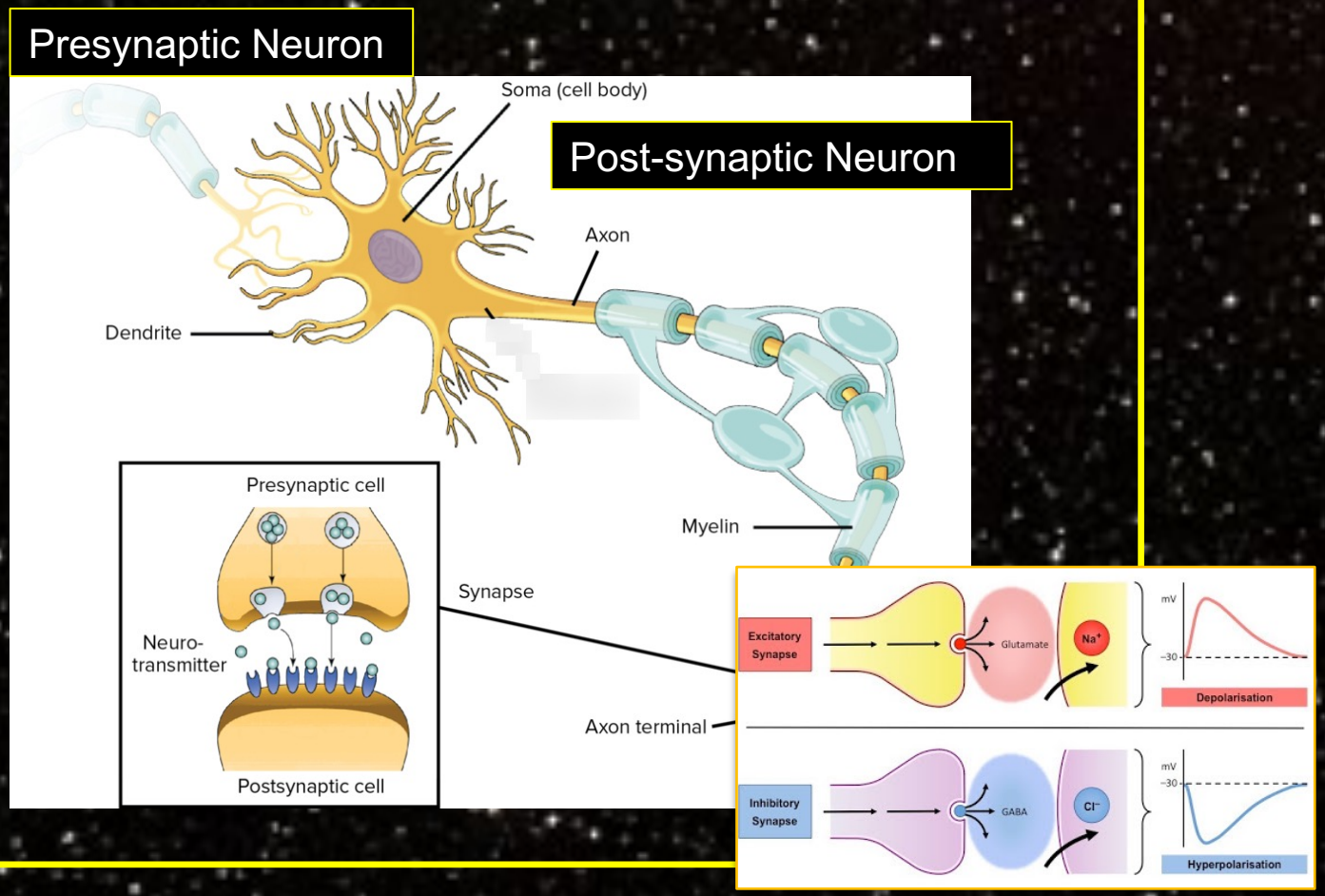
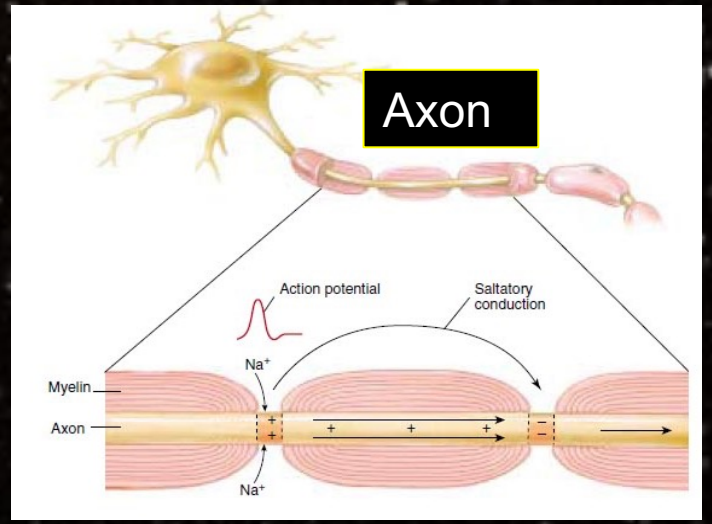
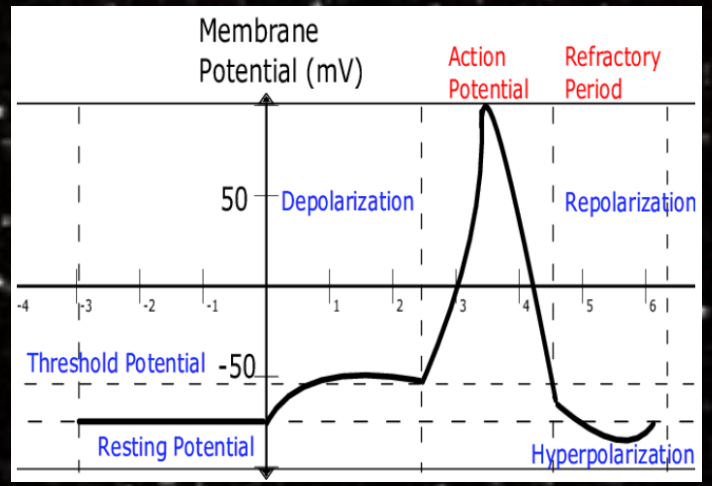
Excitatory and Inhibitory Post-Synaptic Potentials

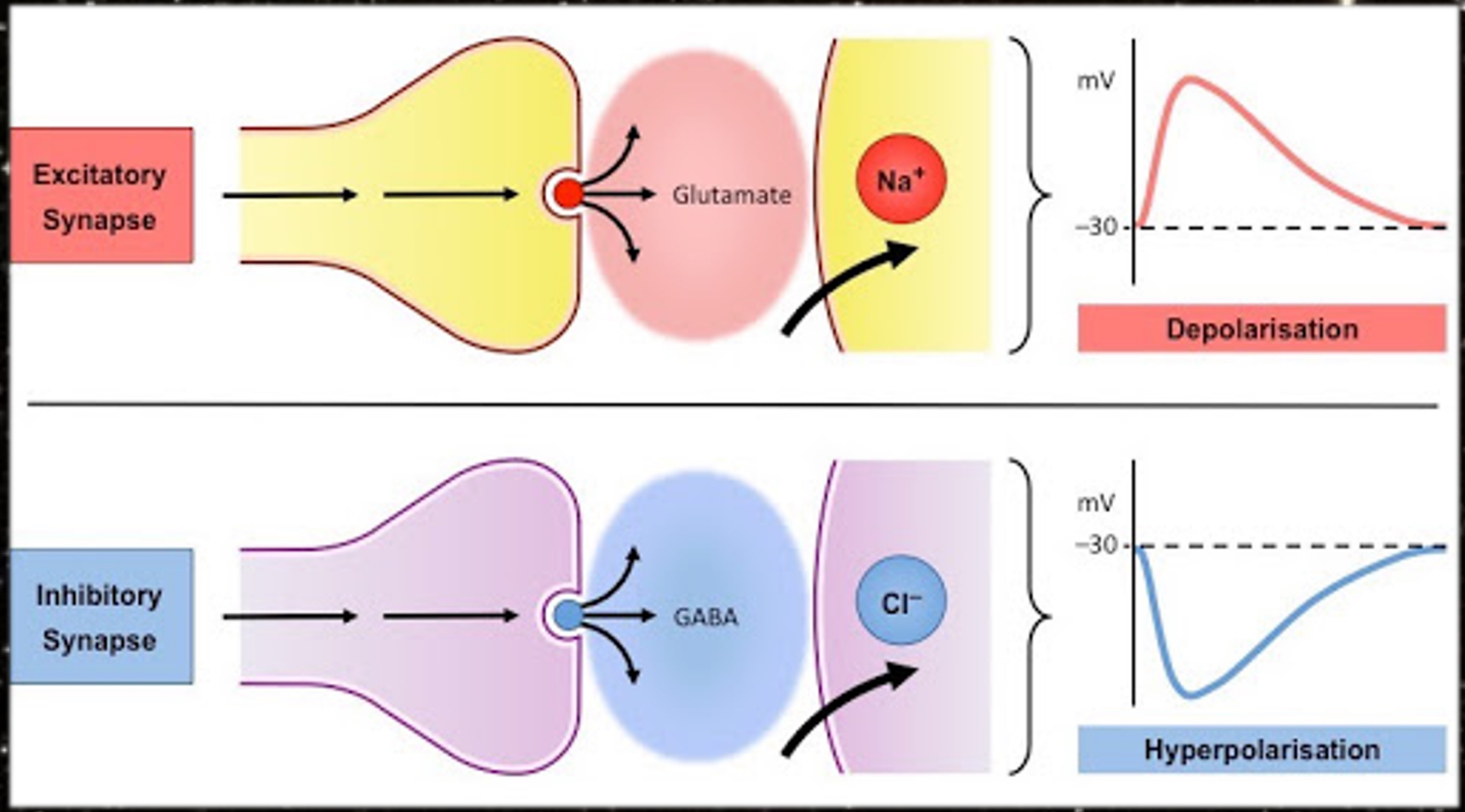


Trains of Action Potentials





Brain Oscillations: Origins



Brain Oscillations:

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Communication-Through-Coherence' (CTC) hypothesis (Fries, 2005)

Intrinsic rhythmic modulations of neuronal excitability

↓

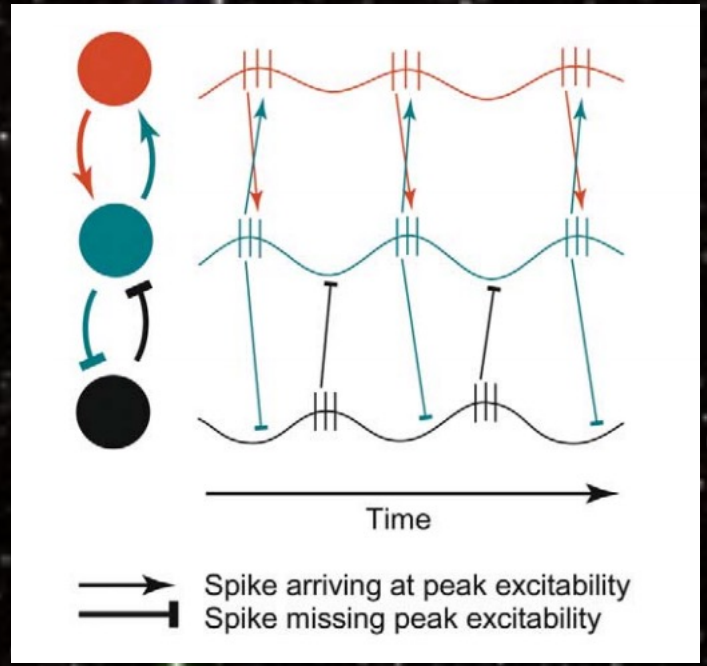
Neuronal excitability affects AP likehood and sensitivity to synaptic inputs

↓

Excitability fluctuations = temporal windows for efficient communication…

↓

To communicate effectivity, neurons oscillatory activity needs to be phase-locked or « coherent ».



Brain Oscillations: Neural Synchrony

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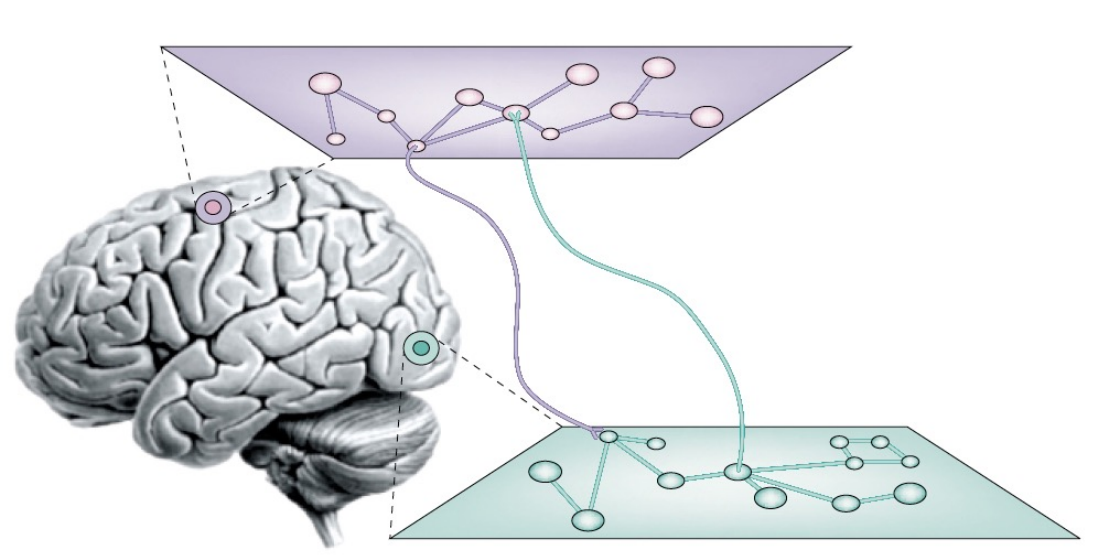
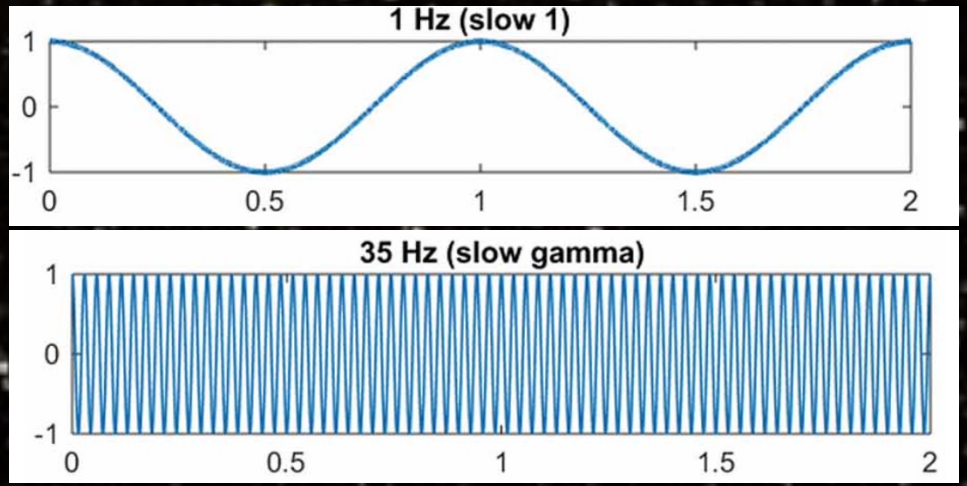
Relationship between the distance over which synchronization is observed and the frequency of the synchronized oscillations:

- **Short-distance synchronization** → higher frequencies (gamma-band) ,
- **Long-distance synchronization** → lower frequencies such as beta, alpha and theta.





Varela et al, 2001, Nature Review Neuroscience.

Brain Oscillations: Summary

So from studies of neural activity have shown:

- The synchronisation of neural populations via rhythmic modulations of excitability states underlies cortical oscillations.
- Information flow between different brain areas can be orchestrated in time by the synchronisation of neuronal output.
- Brain oscillations observed during cognitive task performance…

But are they causally relevant or a by-product?

Brain Oscillations: Studying their role in human cognition

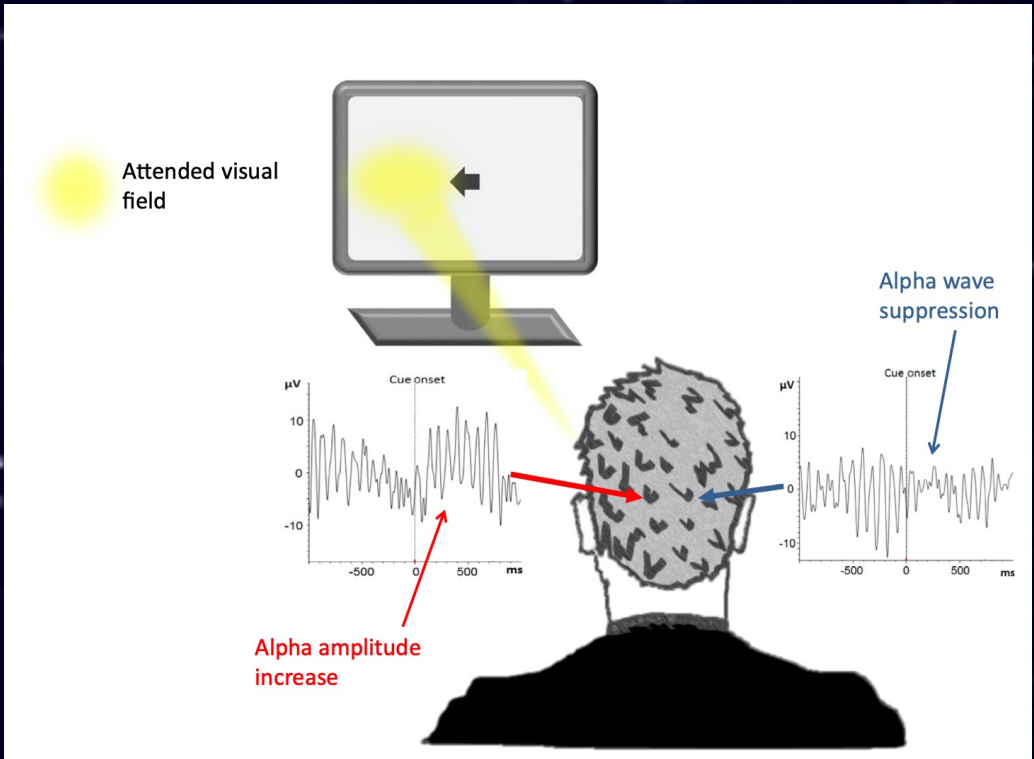
Isolate brain oscillations associated with a task using MEG and EEG

Use Transcranial Magentic Stimulation (TMS) to induce frequency-specific activity in the brain – modulate task performance.

https://brainclinics.com/rtms/

Brain Oscillations: Studying their role in human cognition

Modulations of alpha activity reflect shifts of visuospatial attention.



Peylo et al, 2021, TINS.

Right parietal-occipital alpha – increases in response to left attention shifts.

Right parietal occipital alpha – decreases in response to right attention shifts.
(*Sauseng et al, 2005*)

Romei et al, 2010:
Modulated target visibility by inducing alpha-like oscillations using TMS.

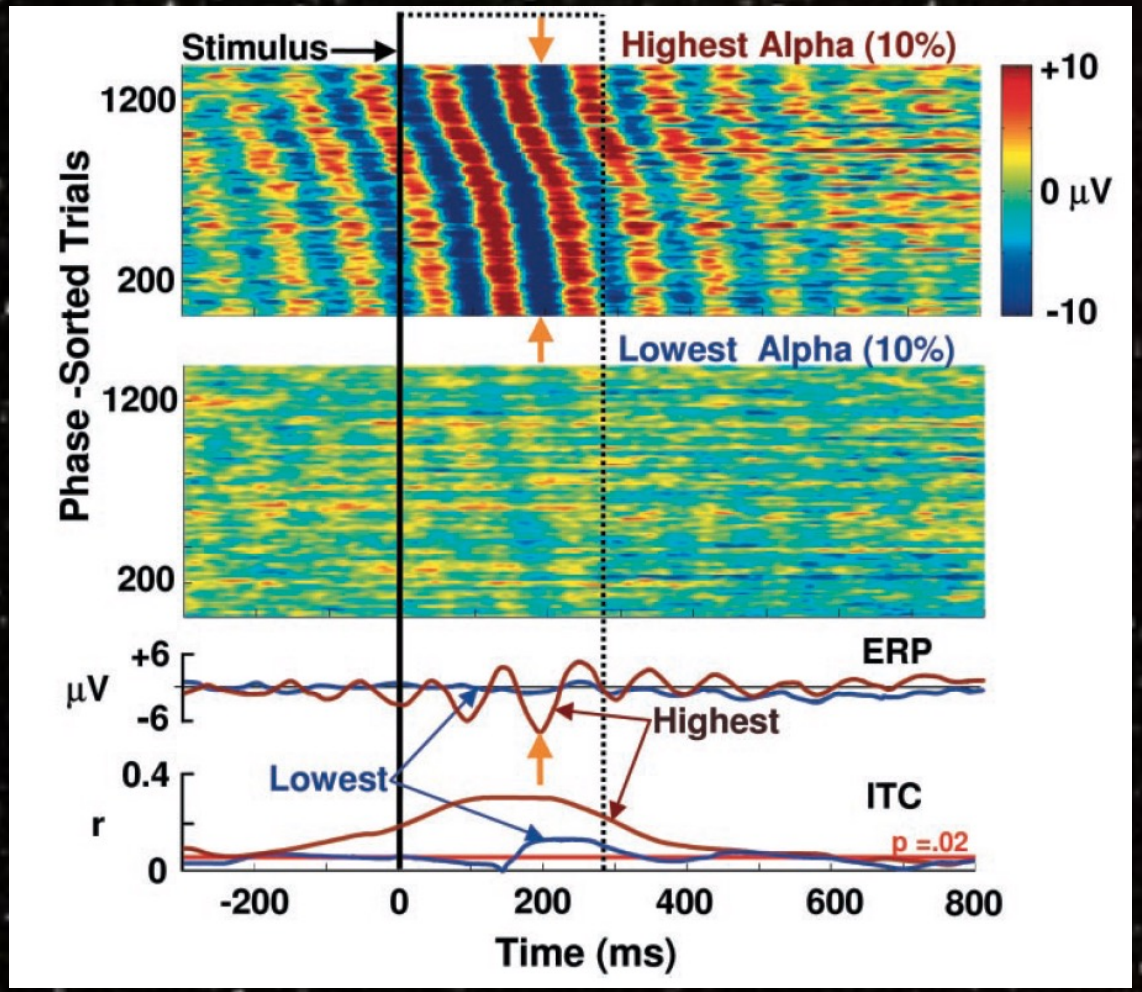
Brain Oscillations:
Implications for EEG Analysis

As oscillations are ongoing phenomena that continue in the absence of experimental task

A change in oscillatory activity related to an event, while time-locked to the event, is not necessarily »**phase-locked** » to it.

The phase of the response in relation to the stimulus varies from **trial to trial**

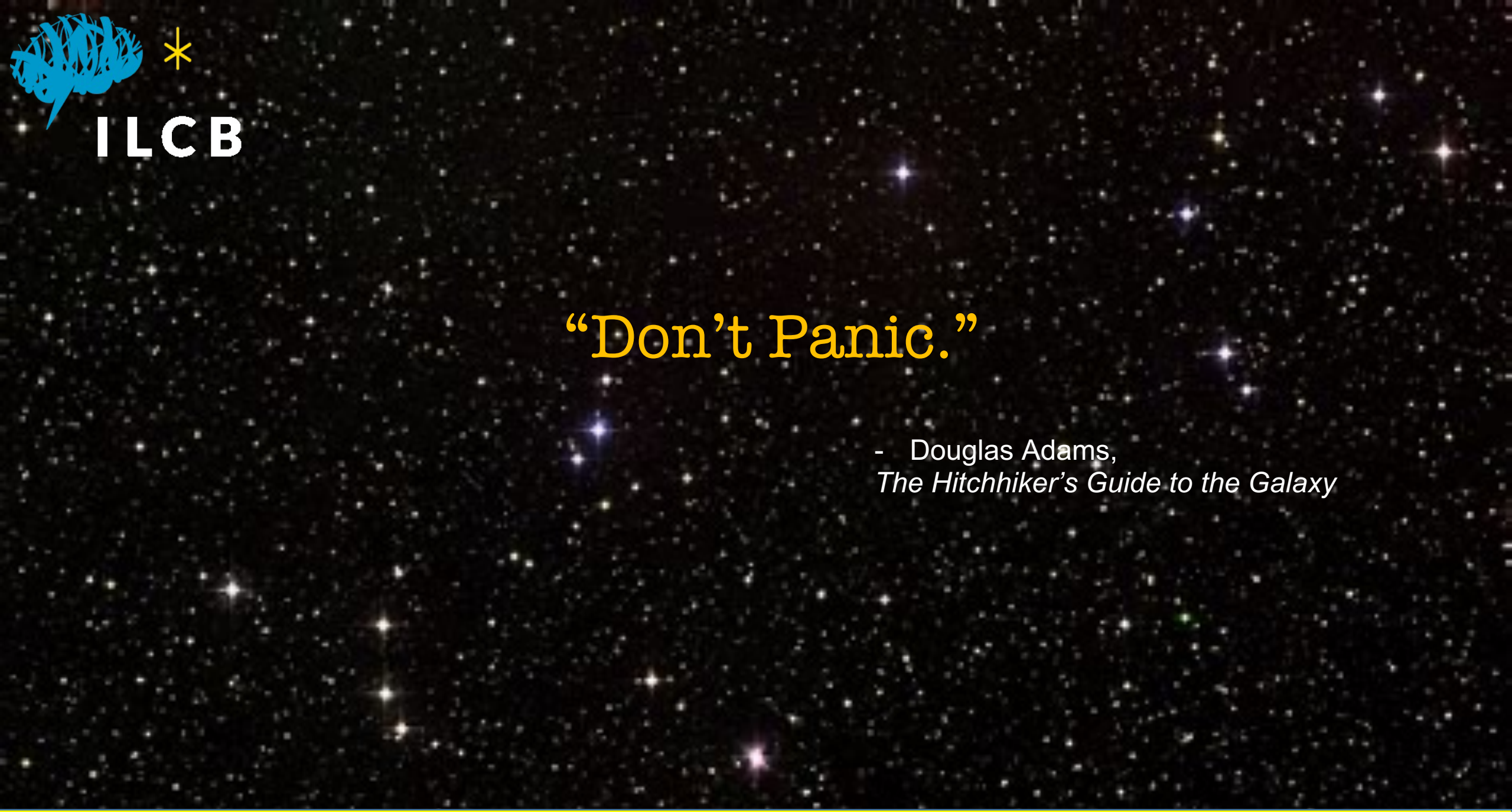
Brain Oscillations: Implications for ERP Analysis



When the pre-stimulus alpha was high, the evoked response amplitude was high...

Makeig et al, 2002, Science, 295, p692.

Measuring Oscillations in EEG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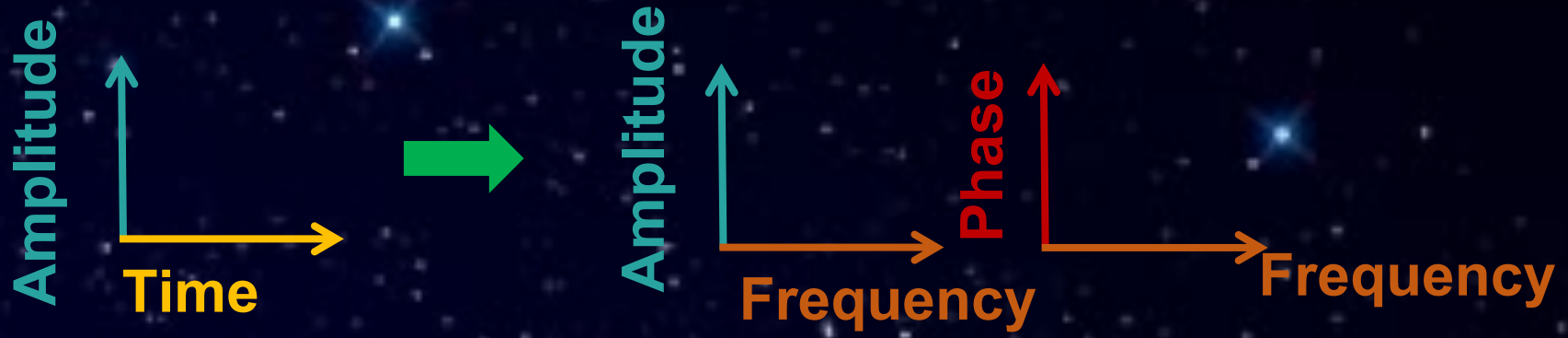
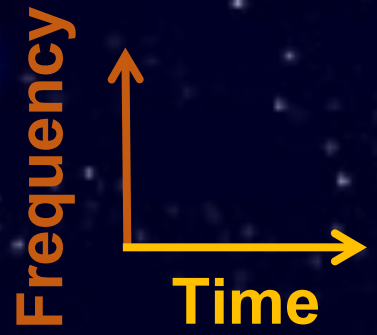
“Don’t Panic.”
- Douglas Adams,
The Hitchhiker’s Guide to the Galaxy

Measuring oscillations in EEG

Spectral analysis



Time-frequency analysis



- ✓ Spontaneous activity
- ✓ Event-related experiment: spectral perturbation relative to the baseline
- ✓ Several estimation methods to get closer to the real time-frequency content

Spectral analysis

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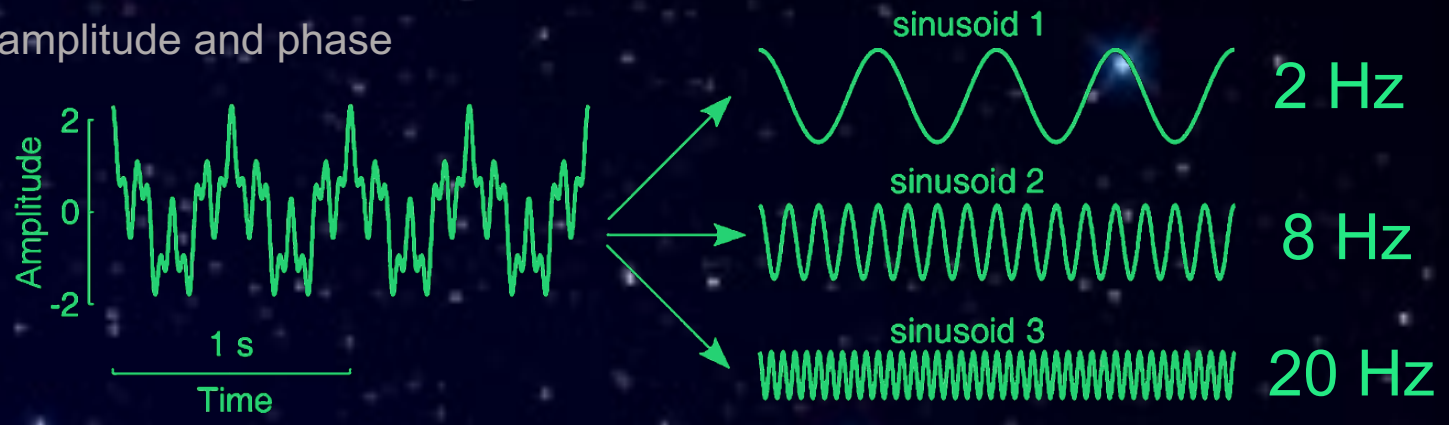
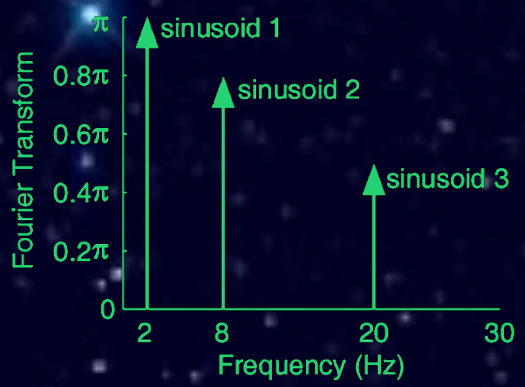
Joseph Fourier,
1768-1830

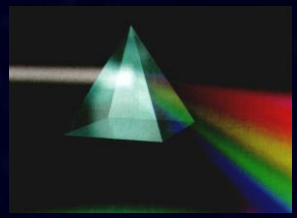
Any continuous periodic signal could be represented as the sum of properly* chosen sinusoidal waves

* of different periods, amplitude and phase



Frequency spectrum





EEG Signal Processing and Feature Extraction, 2019 Li Hu, Springer

Spectral analysis

Finite and discrete time signal

- Discrete Fourier Transform (DFT)

Sinusoidal waves (complex exp notation)

$$X[k] = \frac{1}{N}\sum_{n=0}^{N-1} x[n]\, e^{-j\,2\pi\,k\,n/N}$$

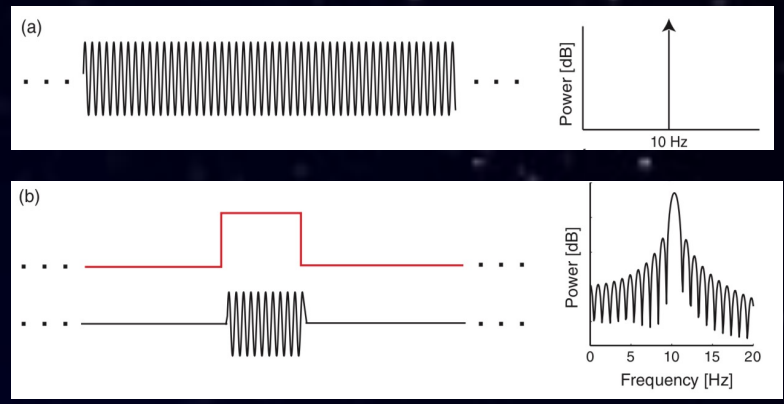
Frequency domain Frequency k

Time domain Sample n

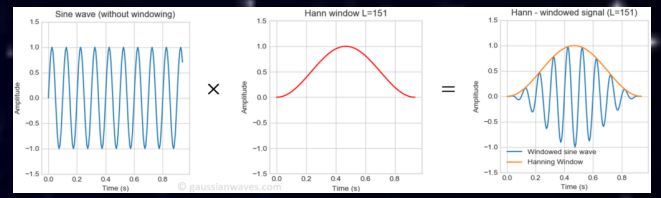
- Fast Fourier Transform (FFT)
  $n^2 \rightarrow (n/2)\ \log2\ (n)$

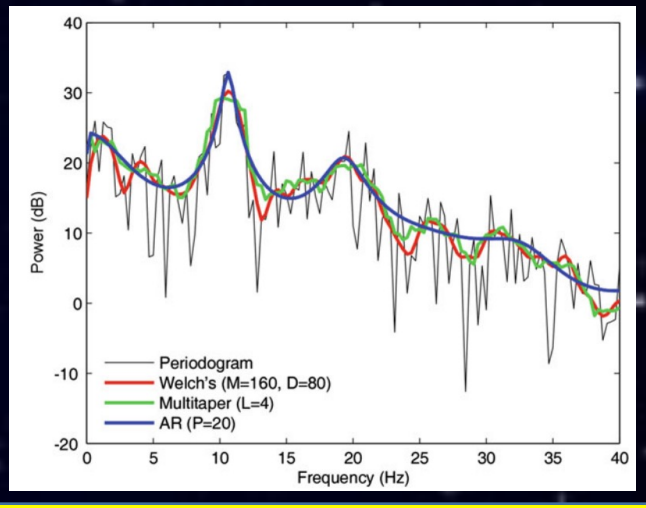
Spectral analysis

Finite and discrete time signal



- Signal x Window function
  - Spectral leakage
  - Windows to reduces discontinuities at the edges
  - Smoothing methods (Welch, Multitaper, Autoregressive model)

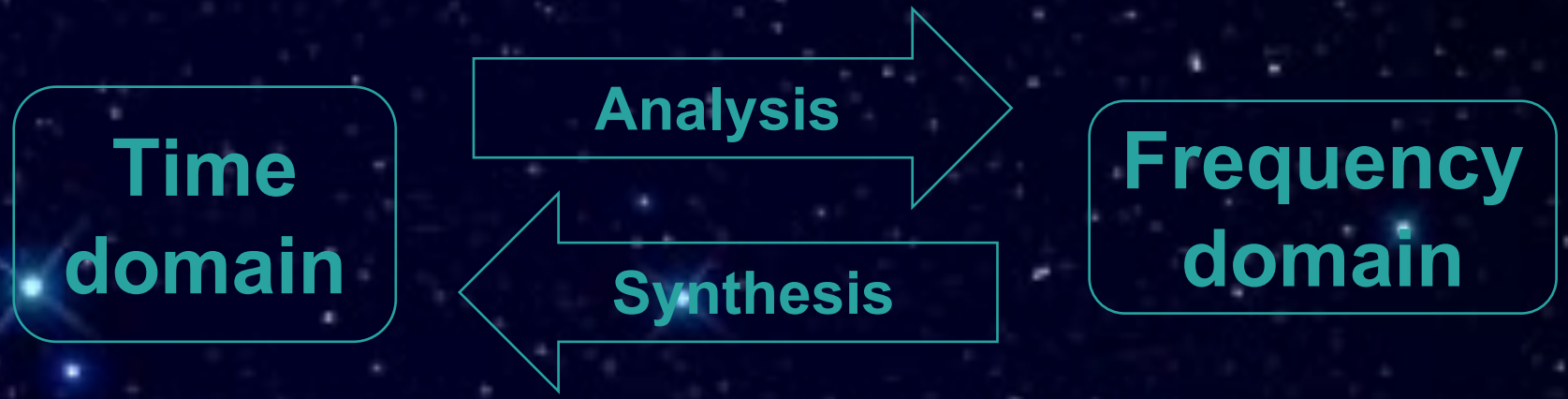


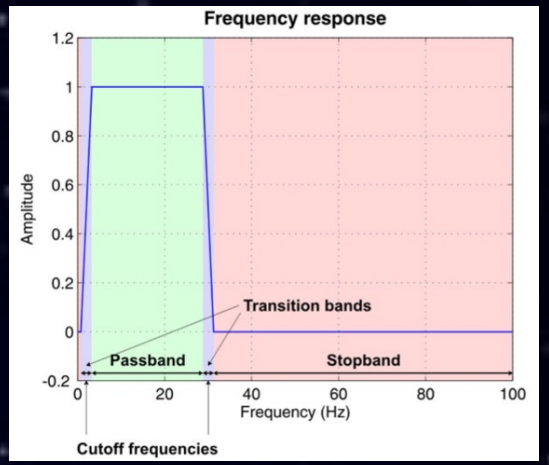


Spectral analysis

Analysis and Synthesis (Inverse DFT)

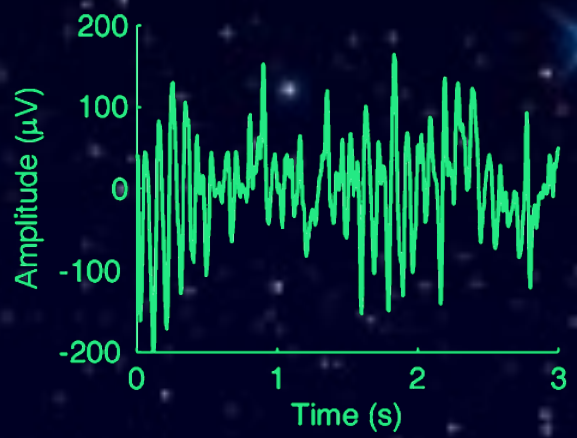
Filtering technic



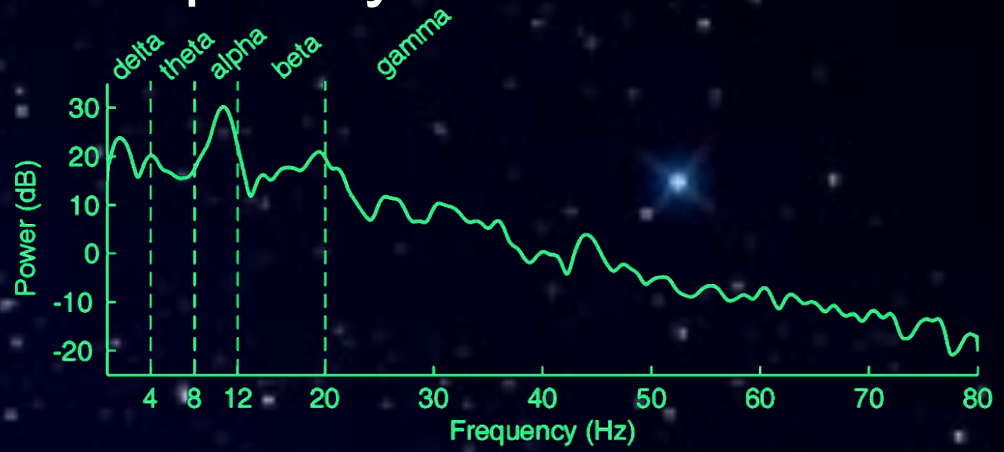


Spectral analysis

Time domain



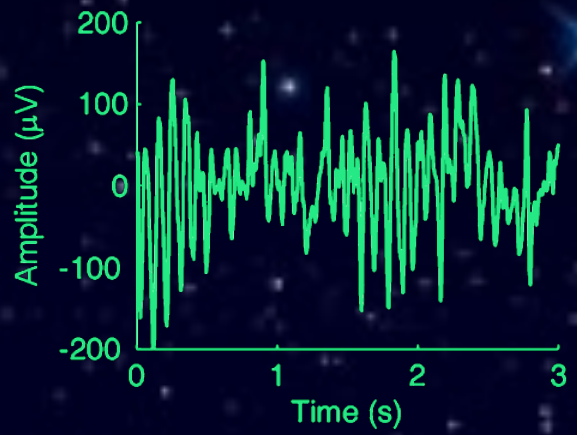
Frequency domain

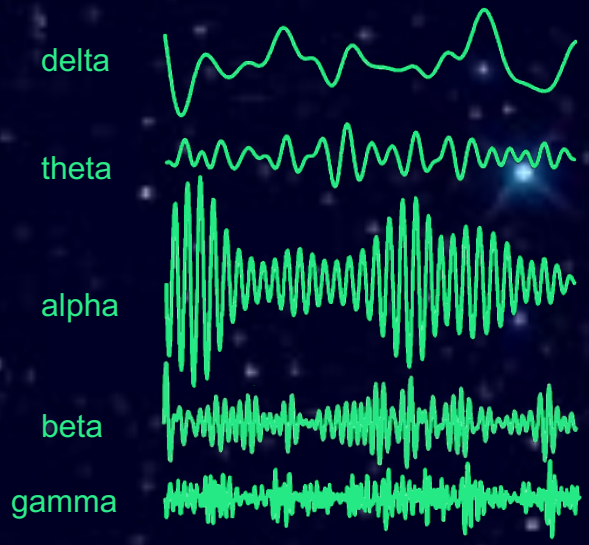


How the signal power is distributed along frequency

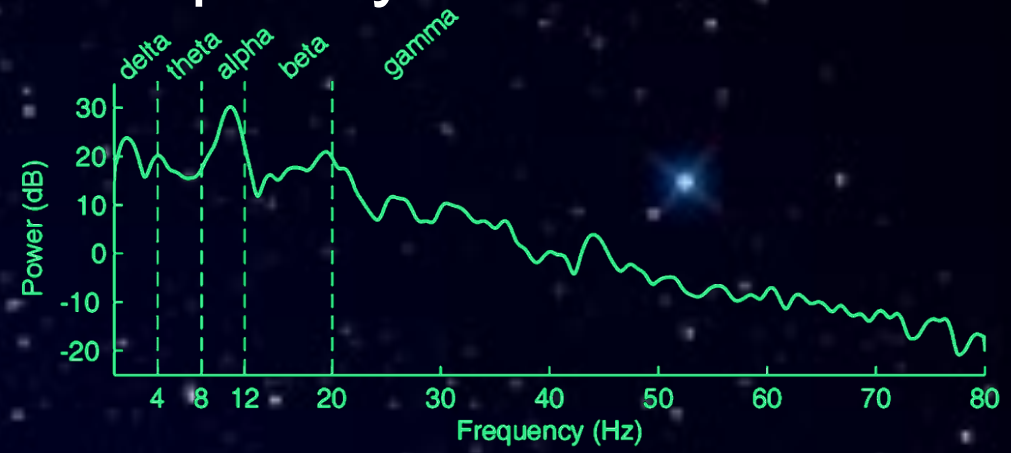
Spectral analysis

Time domain





Frequency domain



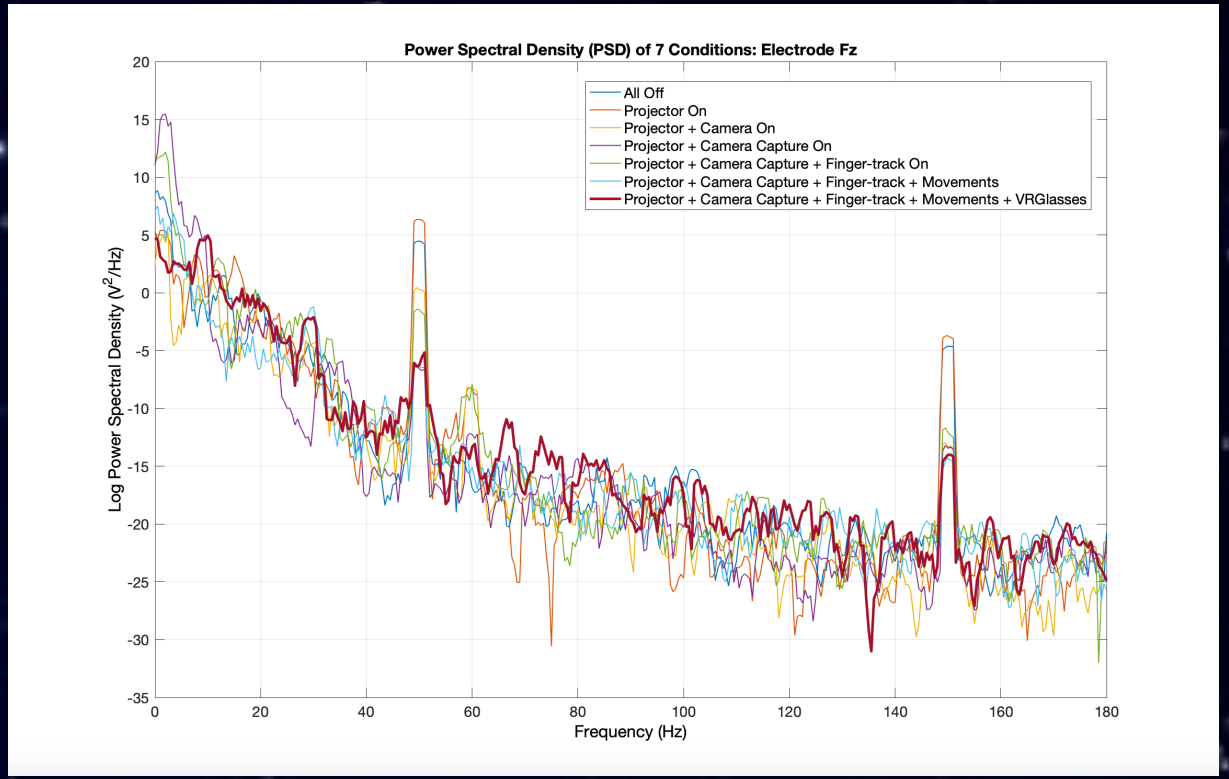
How the signal power is distributed along frequency

10 Hz (10 cycles/second)
Period = 1/f = 0.100 ms

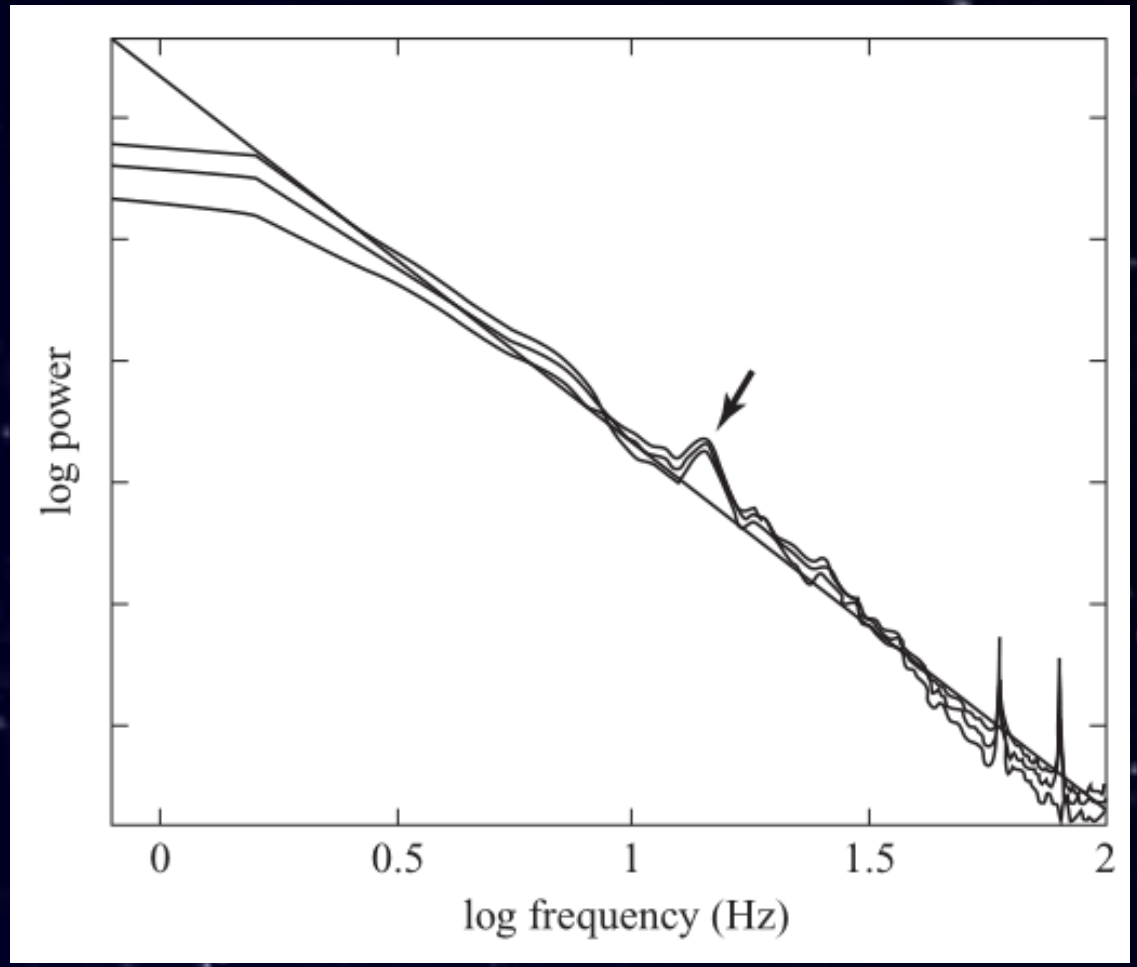
Modulation of the alpha over the time

Decrease of the power in 1/f

Spectral analysis

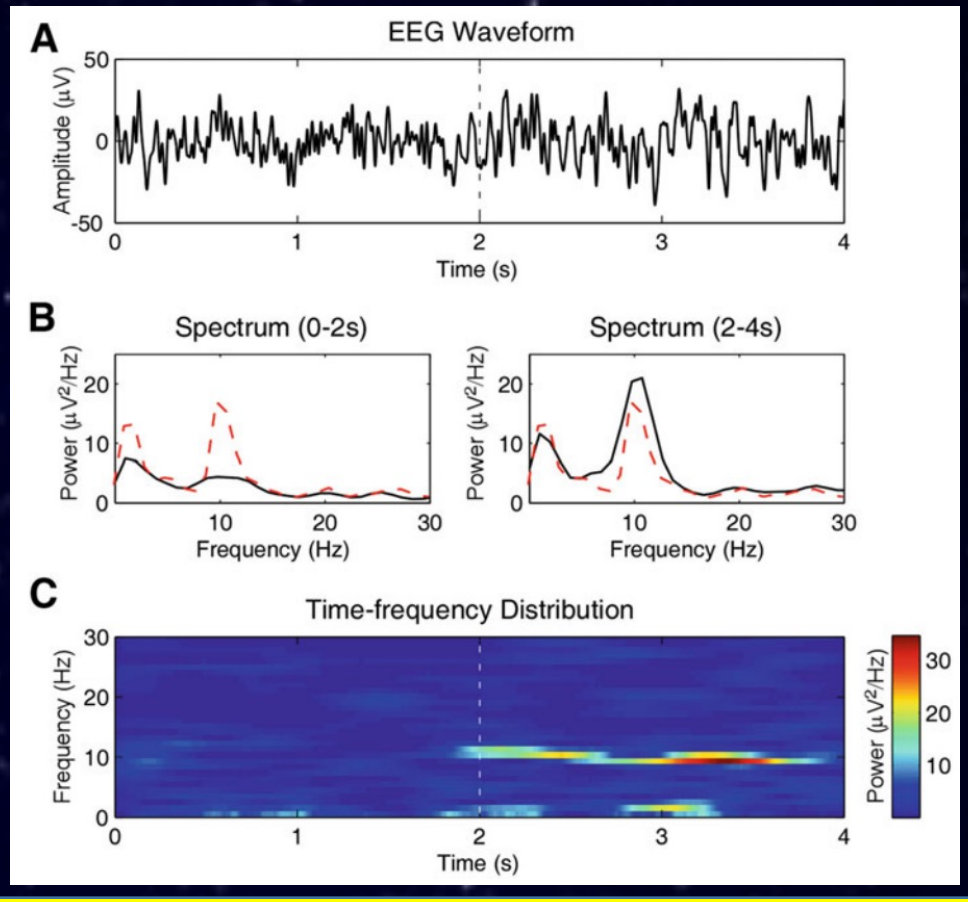


Spectral analysis



Time-frequency analysis

EEG: highly non-stationary
Modulation, transient event (α, β bursts)
Experimental conditions or mental states

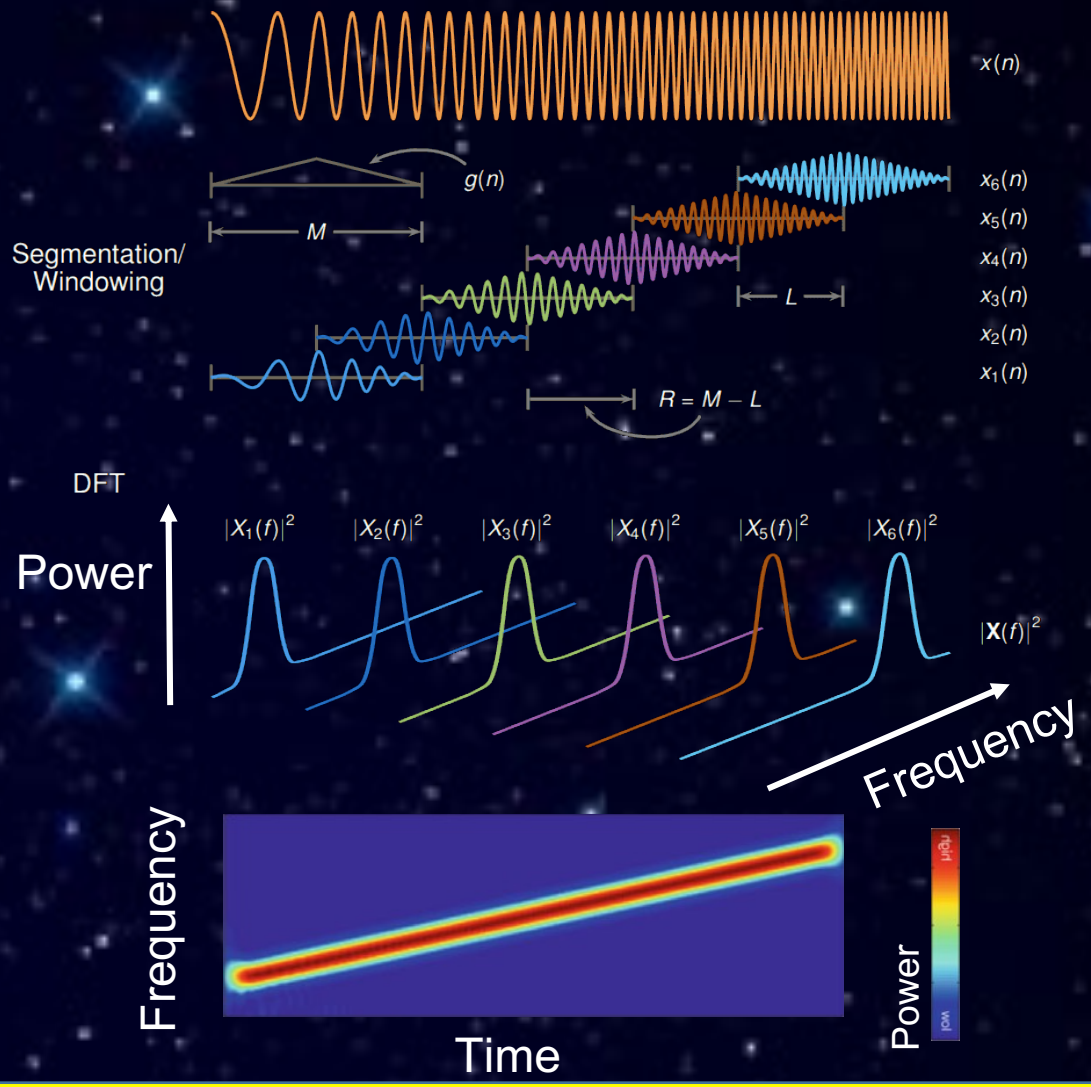


Red: spectrum from total duration

EEG Signal Processing and Feature Extraction, 2019 Li Hu, Springer

Time-frequency analysis

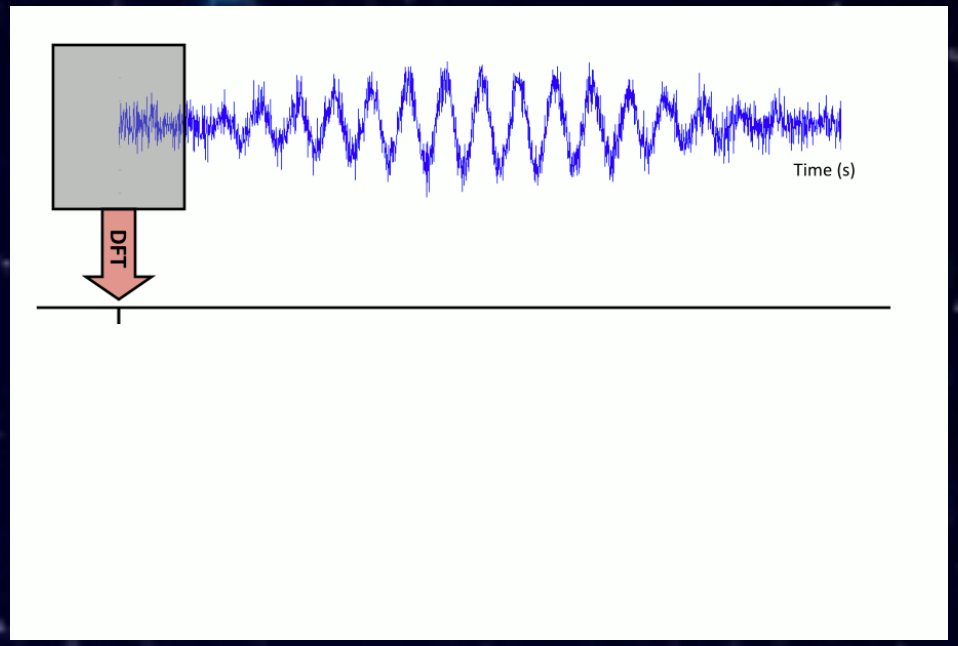
Short-Time Fourier Transform (STFT)



Mathworks

Time-frequency analysis

Short-Time Fourier Transform (STFT)



Robert Oosteostenveld,
Fieldtrip workshop

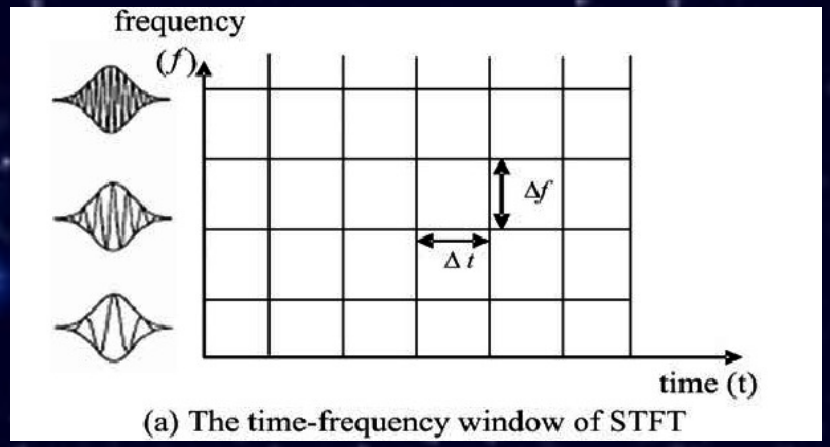
Time-frequency analysis

Width of the analysis window: time resolution

Frequency resolution higher (lowest bin height) with more samples

$$\Delta f = \frac{f_s}{\mathrm{N}}$$

Trade-off $\Delta f \propto \frac{1}{\Delta t}$



Fixed time-frequency resolution

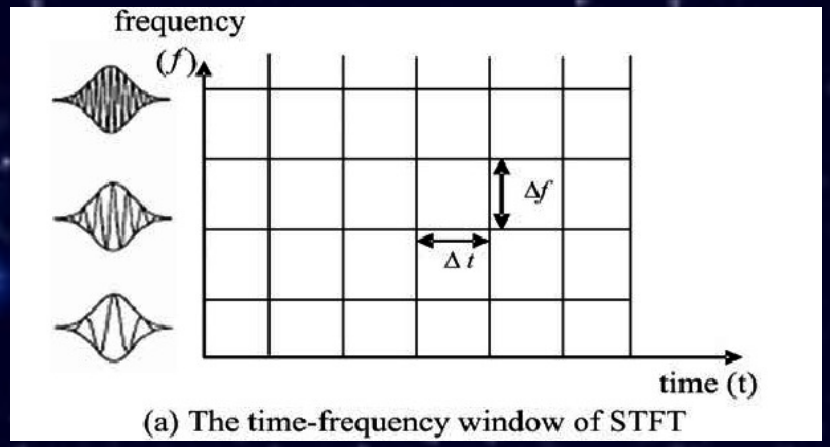
Time-frequency analysis

Width of the analysis window: time resolution

$$\Delta f = \frac{f_s}{\mathrm{N}}$$

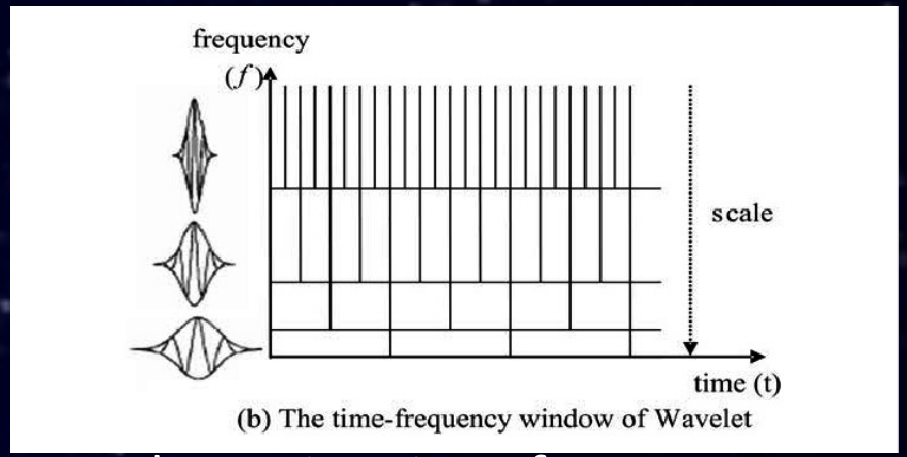
Frequency resolution higher (lowest bin height) with more samples

Trade-off $\Delta f \propto \frac{1}{\Delta t}$



(a) The time-frequency window of STFT

Fixed time-frequency resolution



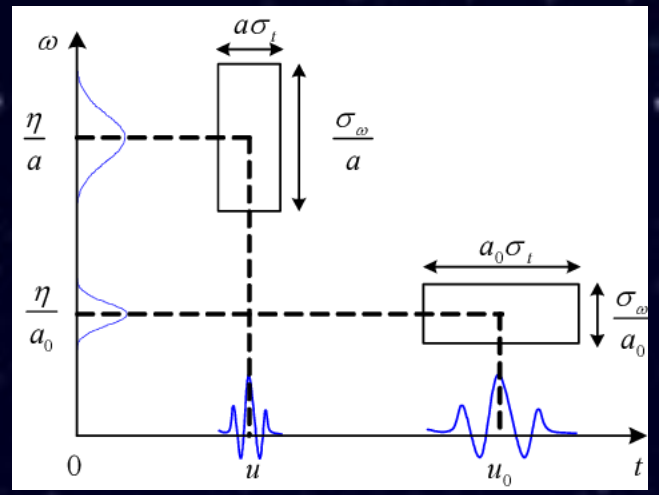
(b) The time-frequency window of Wavelet

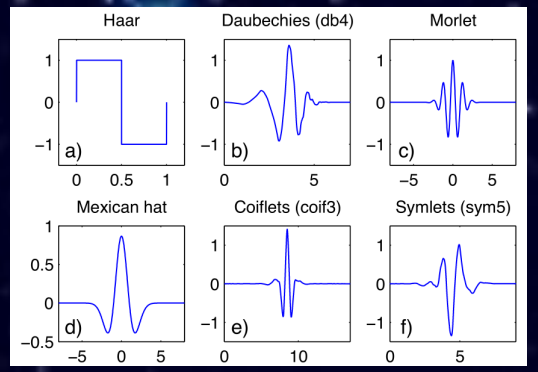
Adaptative time-frequency resolution

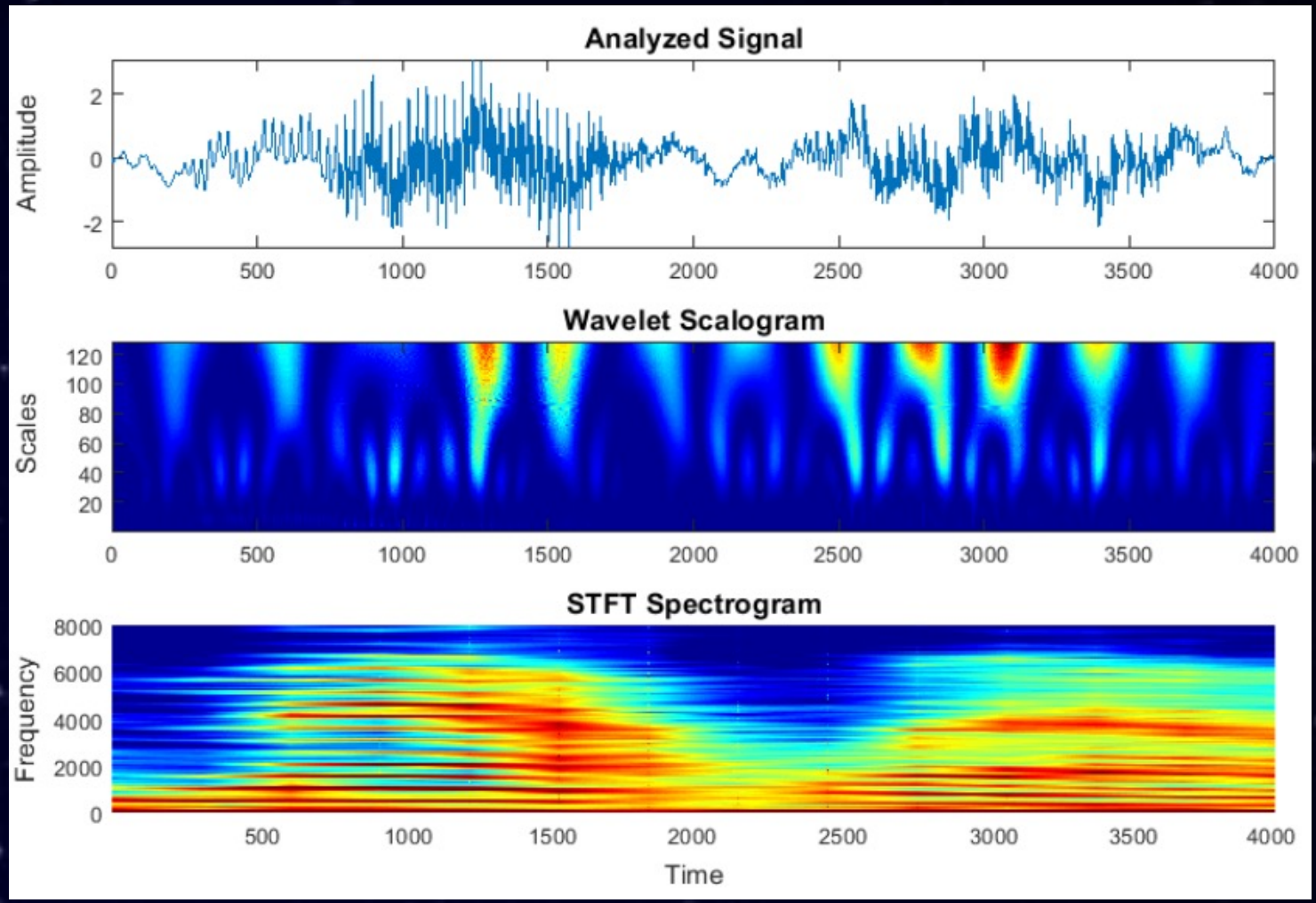
Multitapers, wavelet

Time-frequency analysis

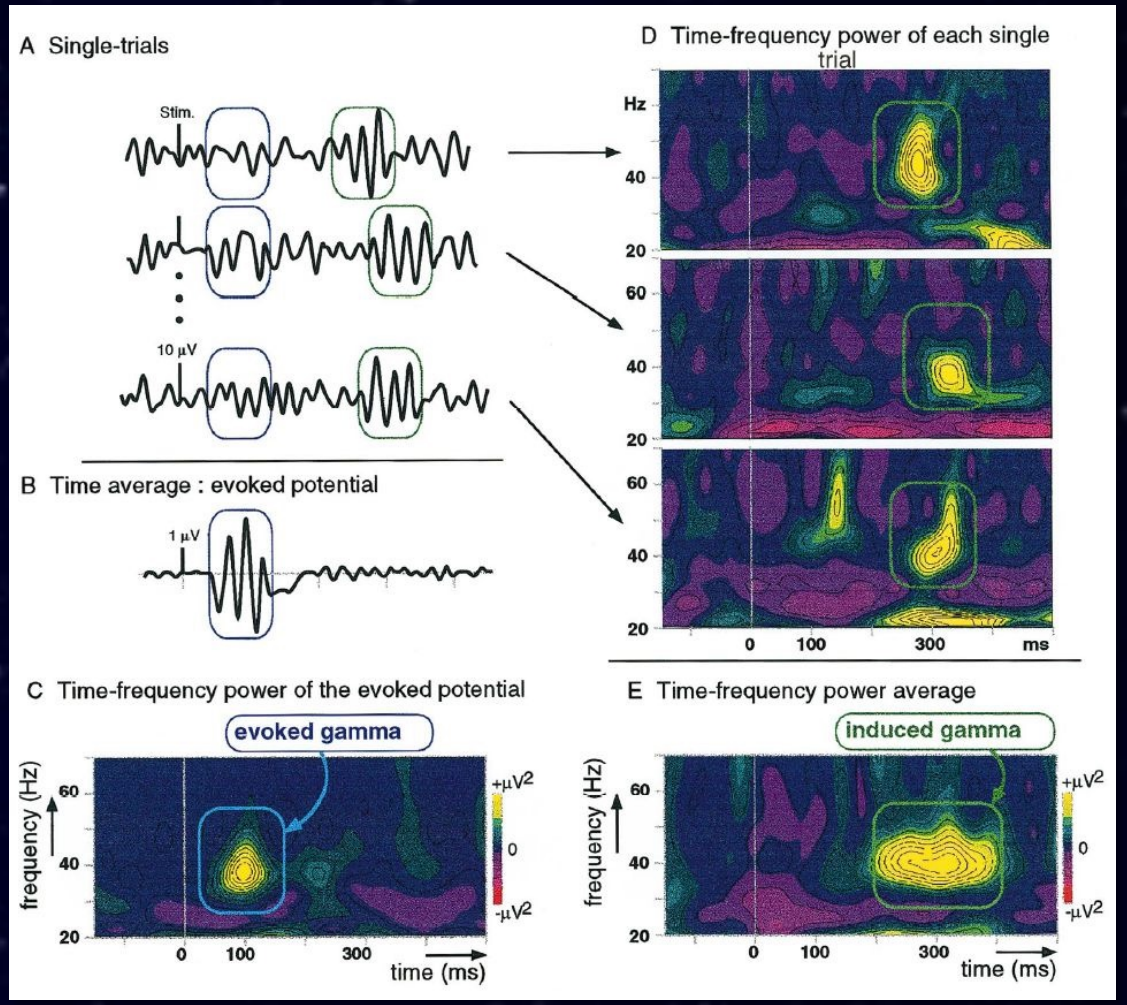
Continuous Wavelet Transform (CWT)







Evoked vs Induced activity



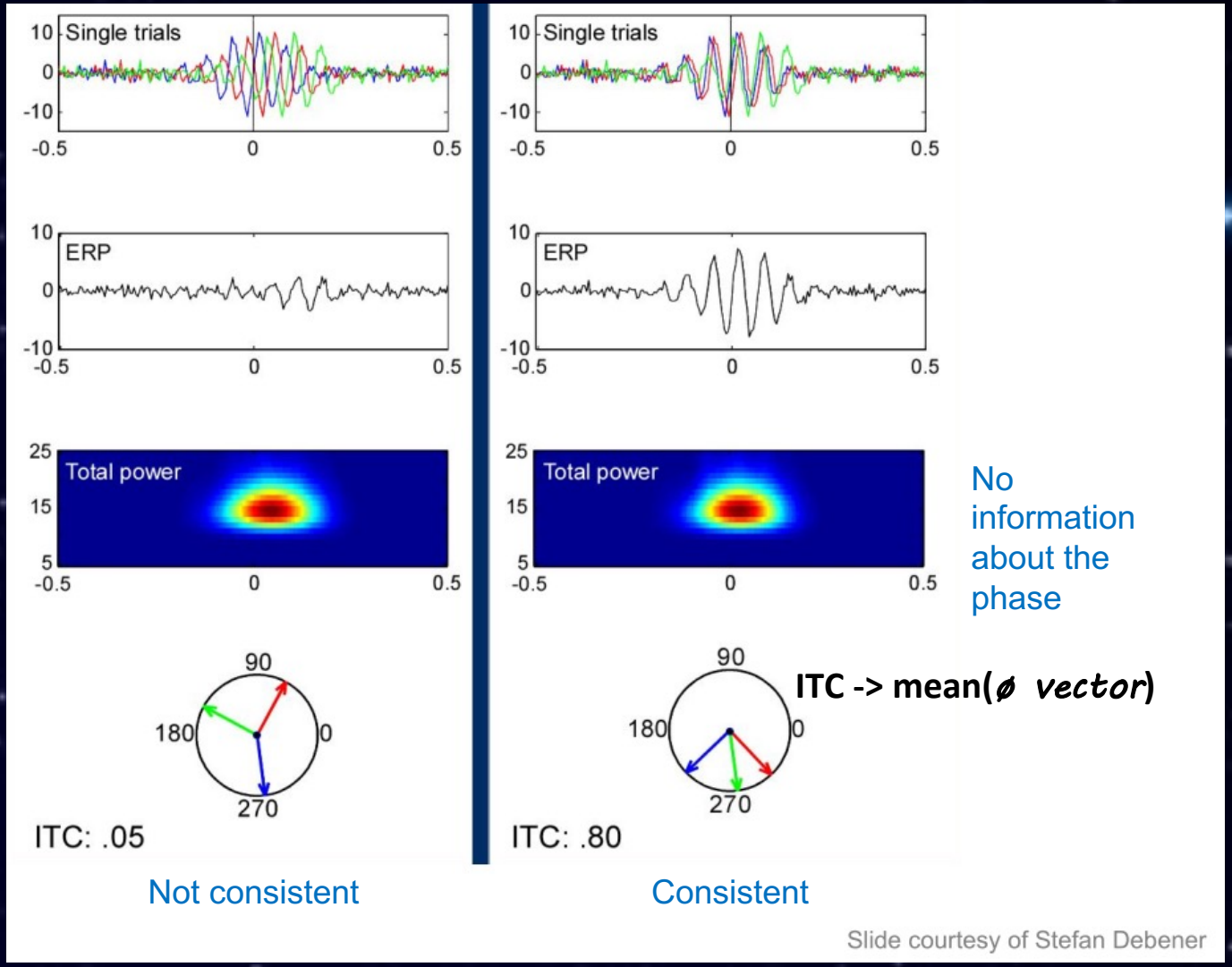
ERP: Time-locked & Phase-locked activity

Time-frequency domain: time-locked

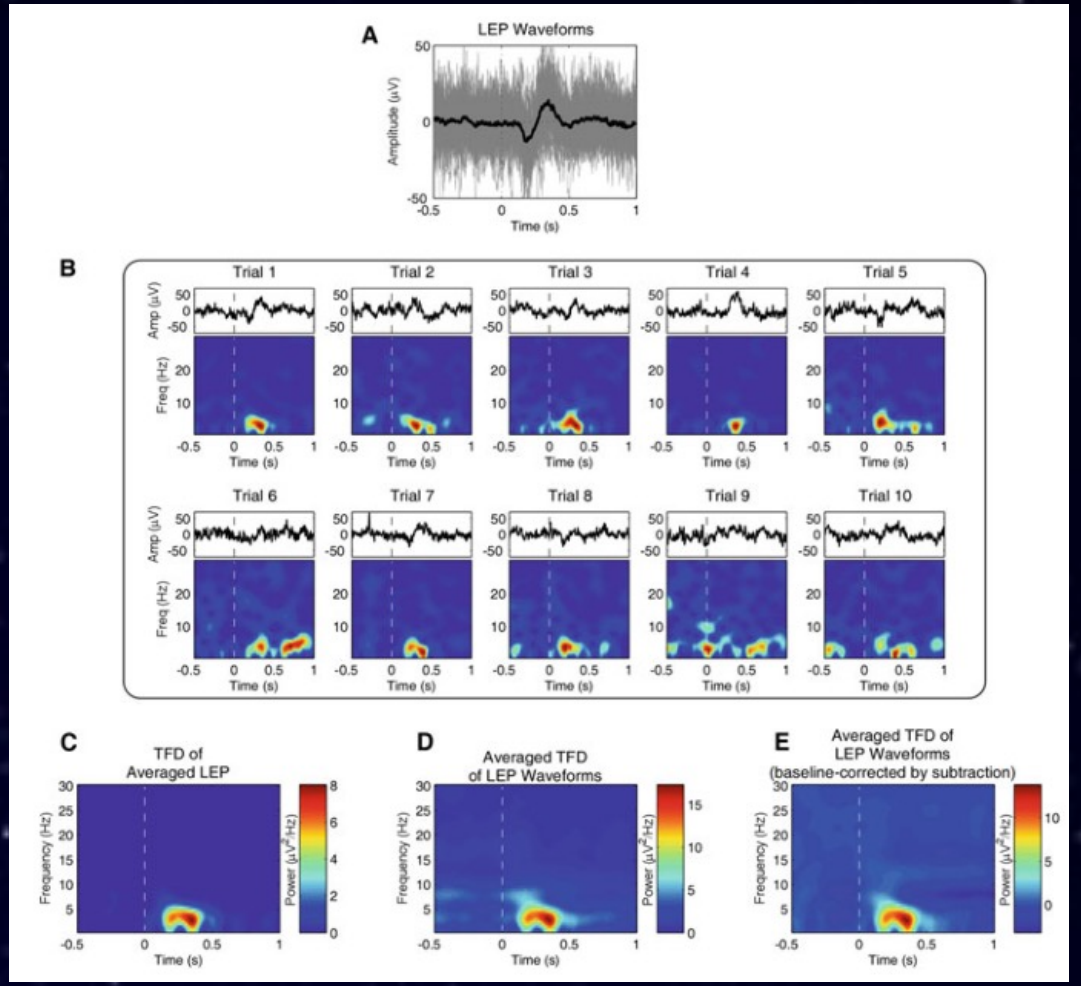
Tallon-Baudry & Bertrand,1999

Inter-trial coherence

Indication of phase consistency across trials



Event-Related Spectral Perturbation



EEG Signal Processing and Feature Extraction, 2019 Li Hu, Springer

Event-Related Spectral Perturbation

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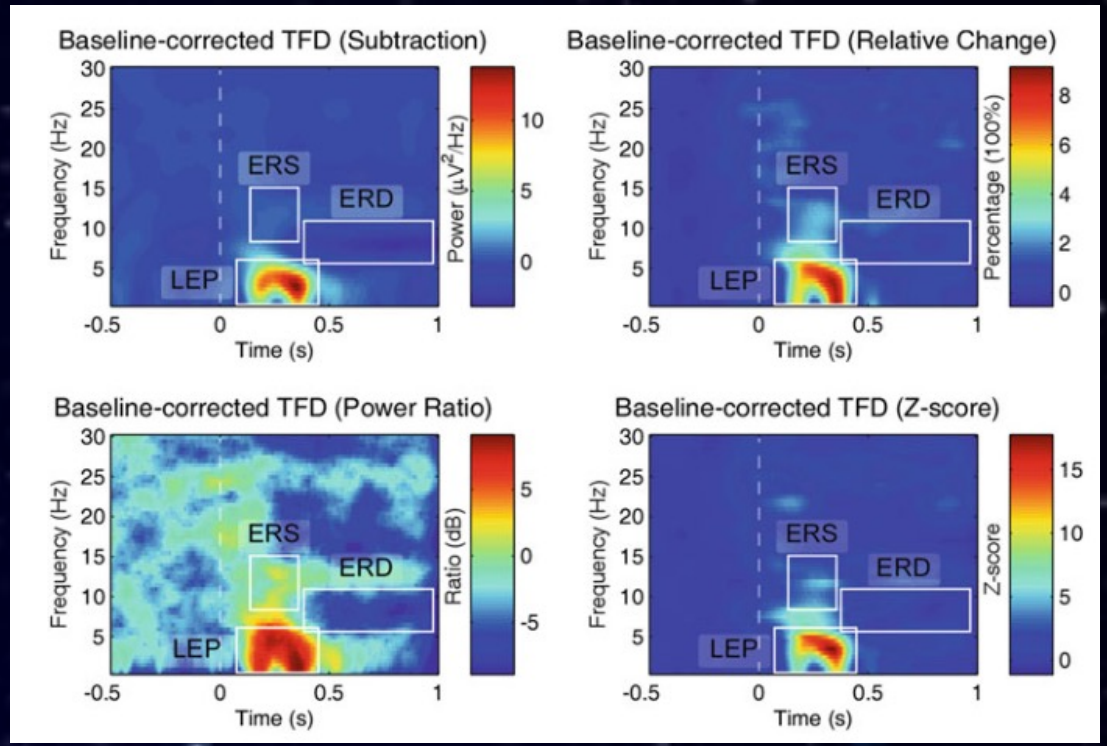
Event-Related Synchronization (ERS) or Desynchronization (ERD)

- considered to be due to a decrease or an increase in synchrony of the underlying neuronal populations (Pfurstcheller et al)
- suggested to reflect cortical activation and deactivation



EEG Signal Processing and Feature Extraction, 2019 Li Hu, Springer

Event-Related Spectral Perturbation

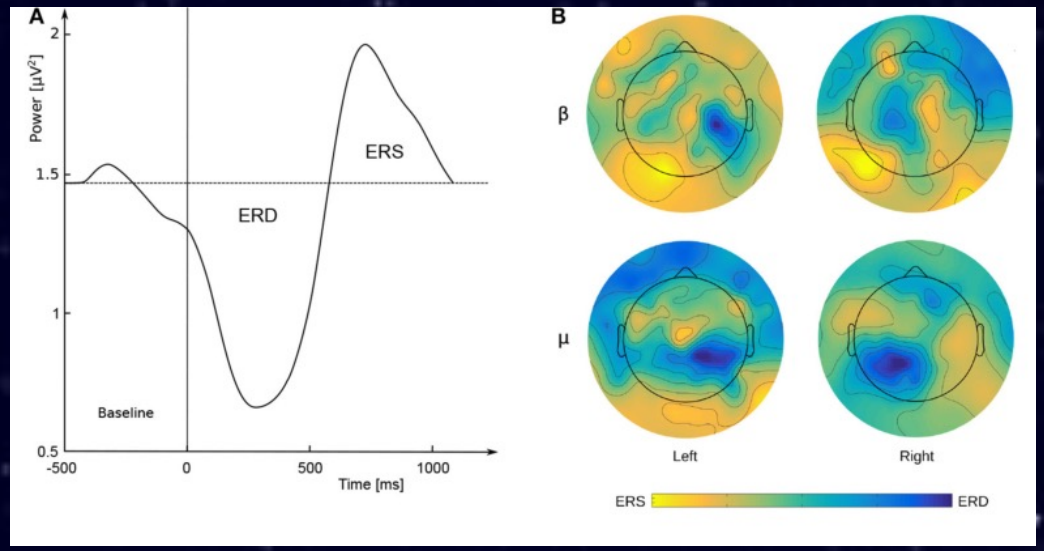
Mental-imagery task

- Mental tasks: motor-imagery of the limb, mental calculation or navigation

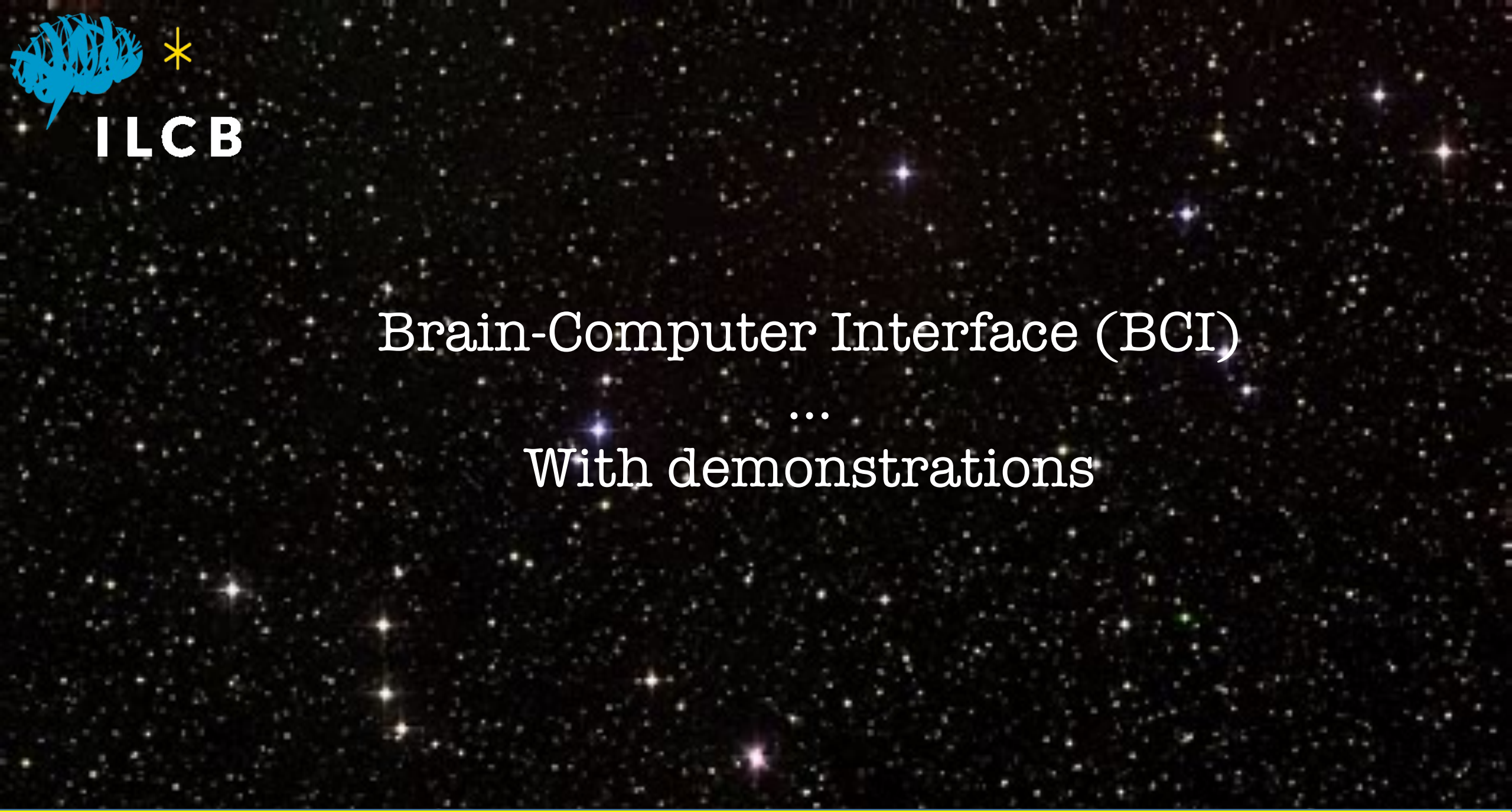
- Induce in specific cortical regions:

1°) Event-Related Desynchronisation (ERD – while being performed)

2°) Event-Related Synchronisation (ERS – once the user has stopped)



Ex. ERD/ERS during motor imagery tasks (Left/Right hand movements)



Brain-Computer Interface (BCI)
…
With demonstrations

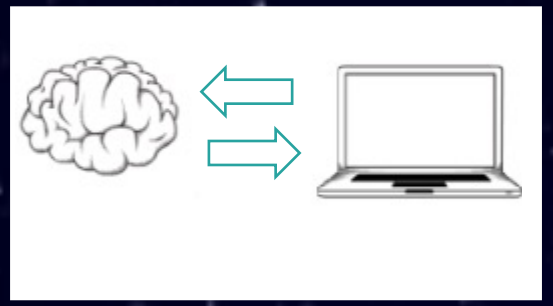
ILCB

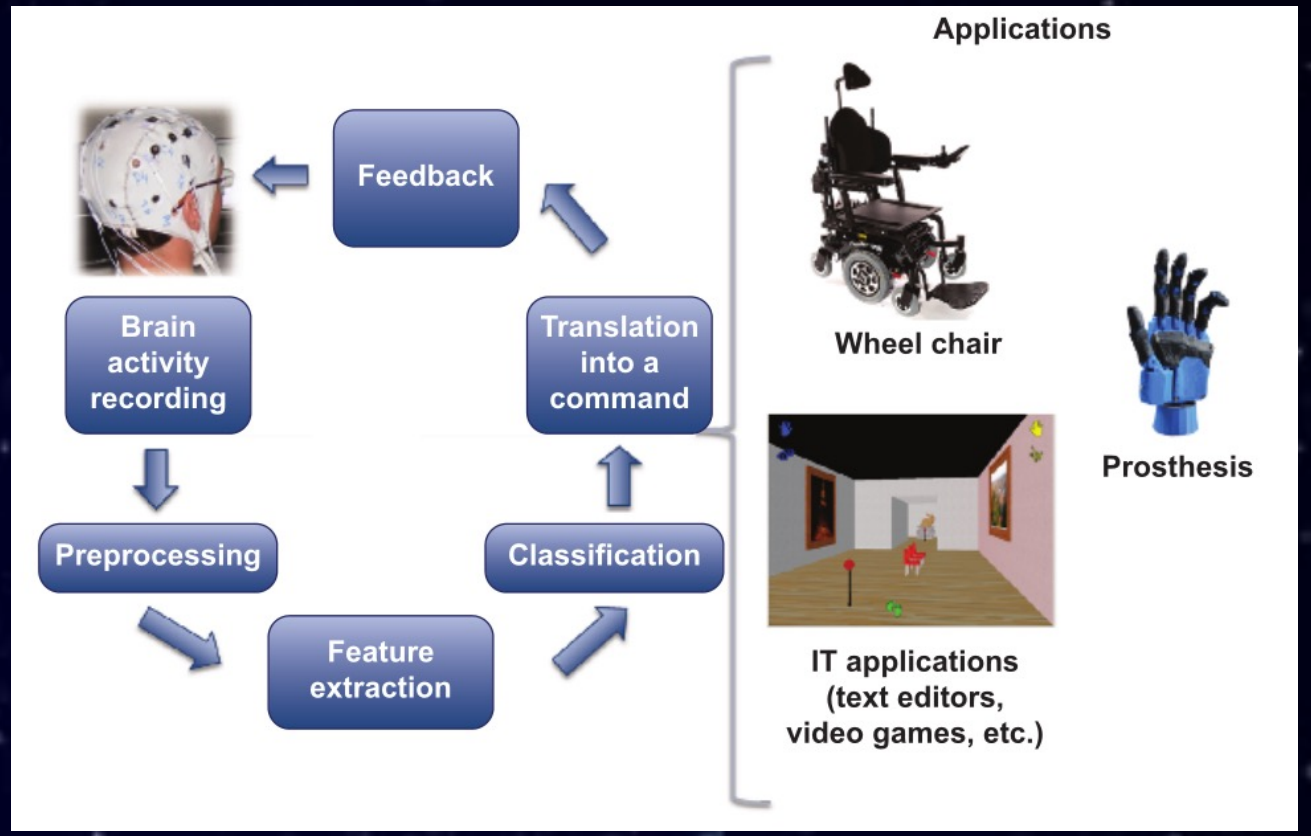
Brain-Computer Interface

"For a moment nothing happened.
Then, after a second or so, nothing continued to happen..."

- Douglas Adams,
The Hitchhiker's Guide to the Galaxy

Brain-Computer Interface



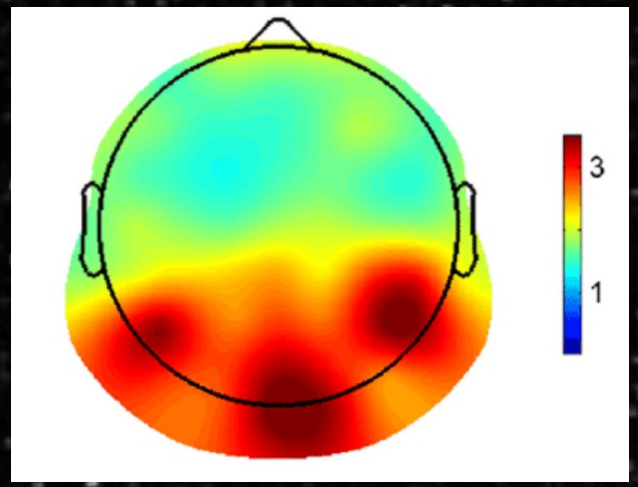


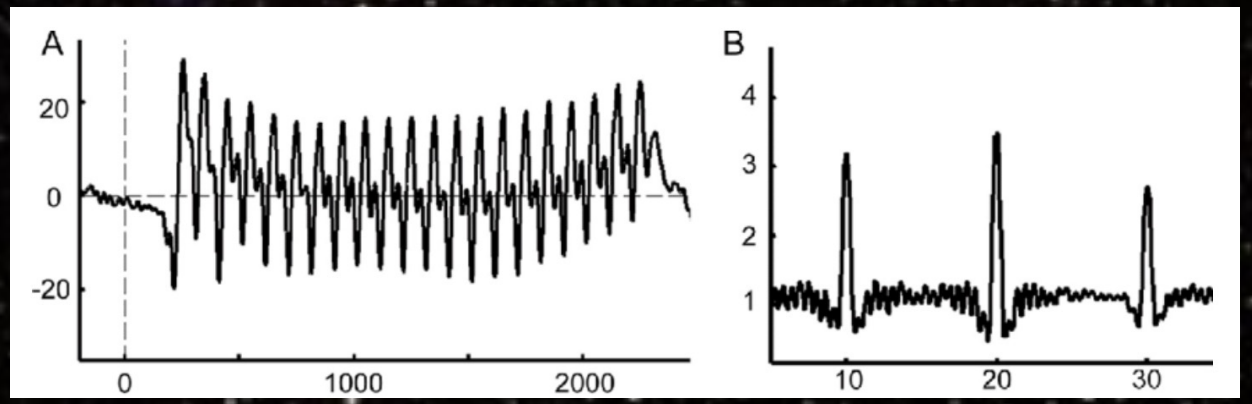
Closed loop systems usually composed of 6 main stages

Steady-State visually evoked potentials (SSVEP)

- SSVEP is a resonance phenomenon.
- Observed mainly in electrodes over the occipital and parietal lobes of brain.
- Generated by a stimuli flickering at a constant frequency ➔ increase in the amplitude of the EEG at flickering frequencies

- The response is both **time** and **phase-locked** to the driving stimulus.





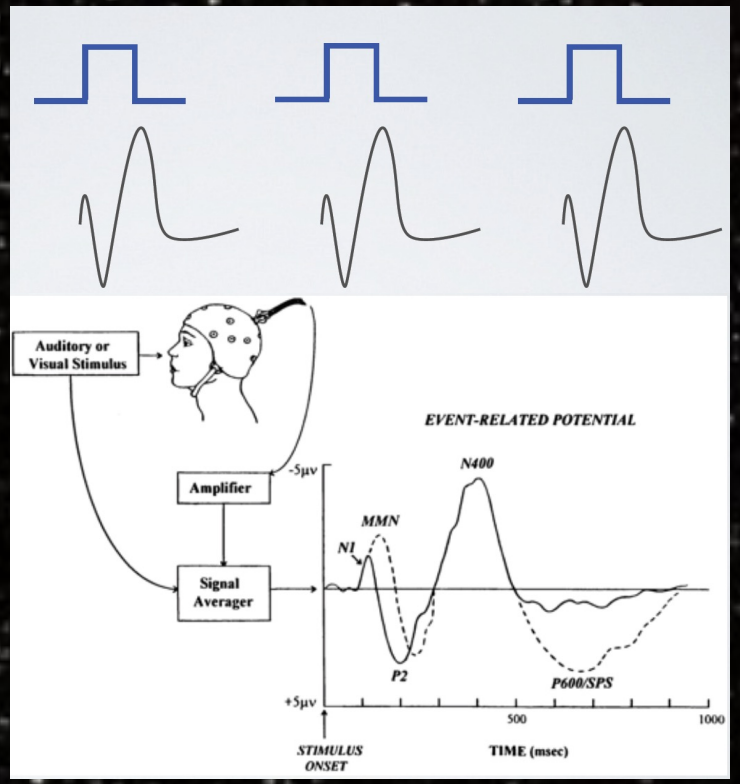
Wang & Yuan, 2021, Neuroscience.

Steady-State Visually Evoked Potentials (SSVEP)

ILCB

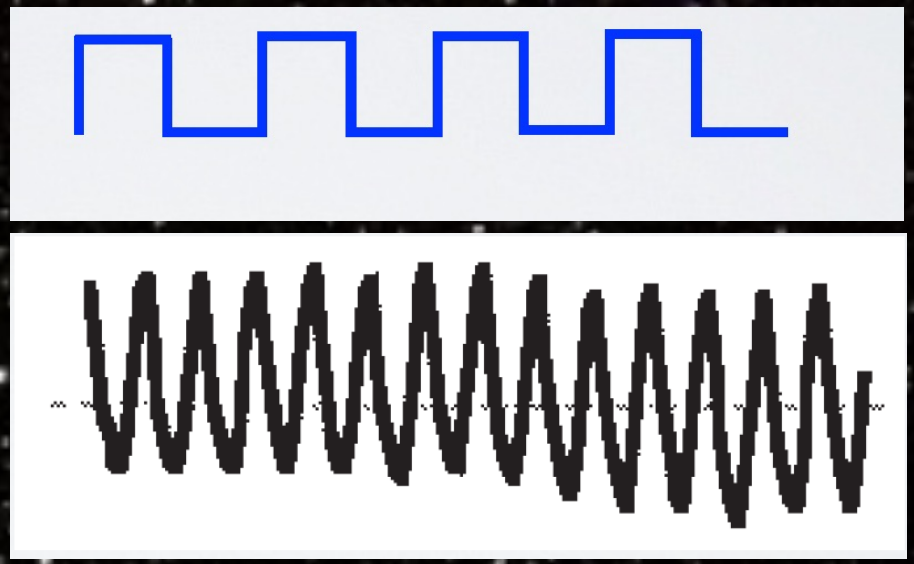
Transient VEP

Very brief stimuli induce **transient** responses:



Steady-state VEP

Modulation of stimulus trains at shorter time-scales induces **entrainment** and a stead-state response.



Muller et al, 1998

Steady-State Visually Evoked Potentials (SSVEP)

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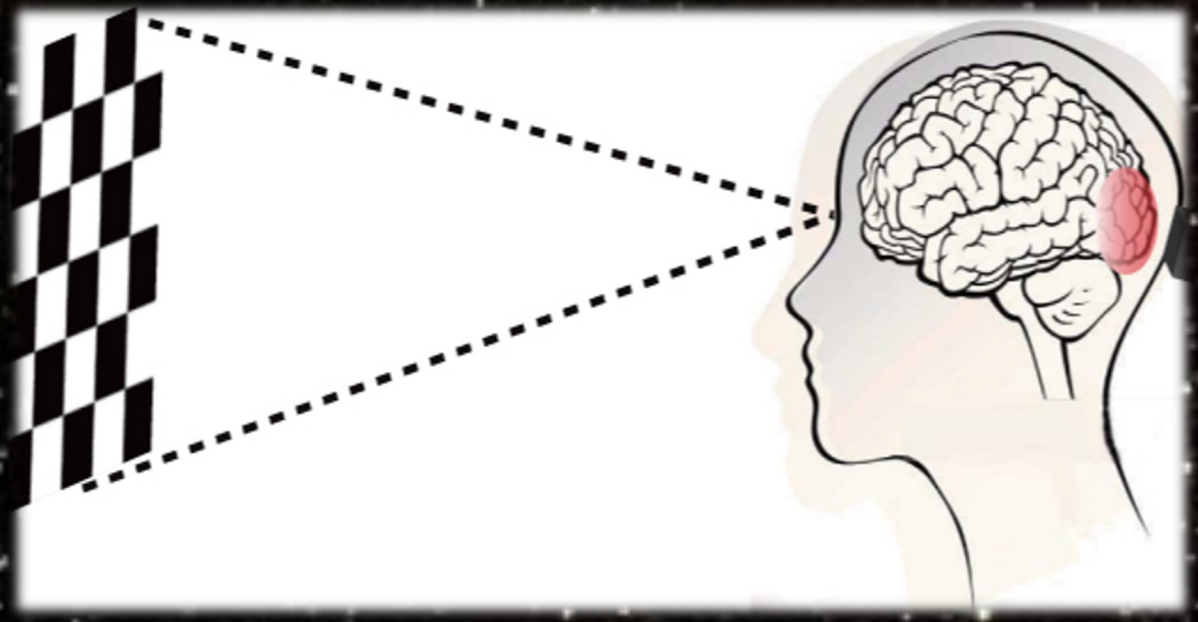


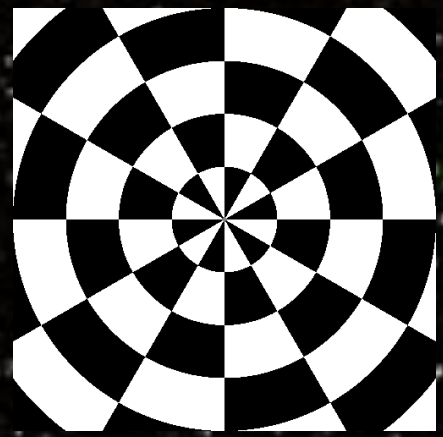
Visual cortex response evoked when the retina of the eye is excited by a visual stimulus

To evoke the SSVEP one has to center his vision on a flashing object.

Stimulation frequencies between 10Hz and 20Hz often provoke the highest amplitude response and have the highest SNR.

Types of stimuli can include:

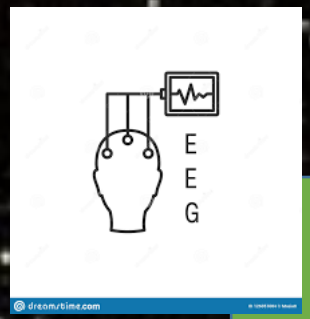
- Flashing LEDs
- Pattern reversal



Steady-State Visually Evoked Potentials (SSVEP)

Visual stimuli generated by **Pygame**

On each SSVEP trial



EEG from OpenBCI via LSL protocol

Oline pre-processing of recorded activity (band-pass filter)

Detection of frequency using Canonical Correlational Analysis

Steady-State Visually Evoked Potentials (SSVEP)

When presenting flickering stimuli on computer screen – stimulus flickering frequency should be a integer divisor of the screen refresh rate:

➔For screen with 60Hz refresh rate flickering frequencies : 30Hz, 20Hz, 15Hz, 12Hz, 10Hz etc...

ILCB

So Long and Thanks for all the Fish

- Douglas Adams,
The Hitchhiker's Guide to the Galaxy