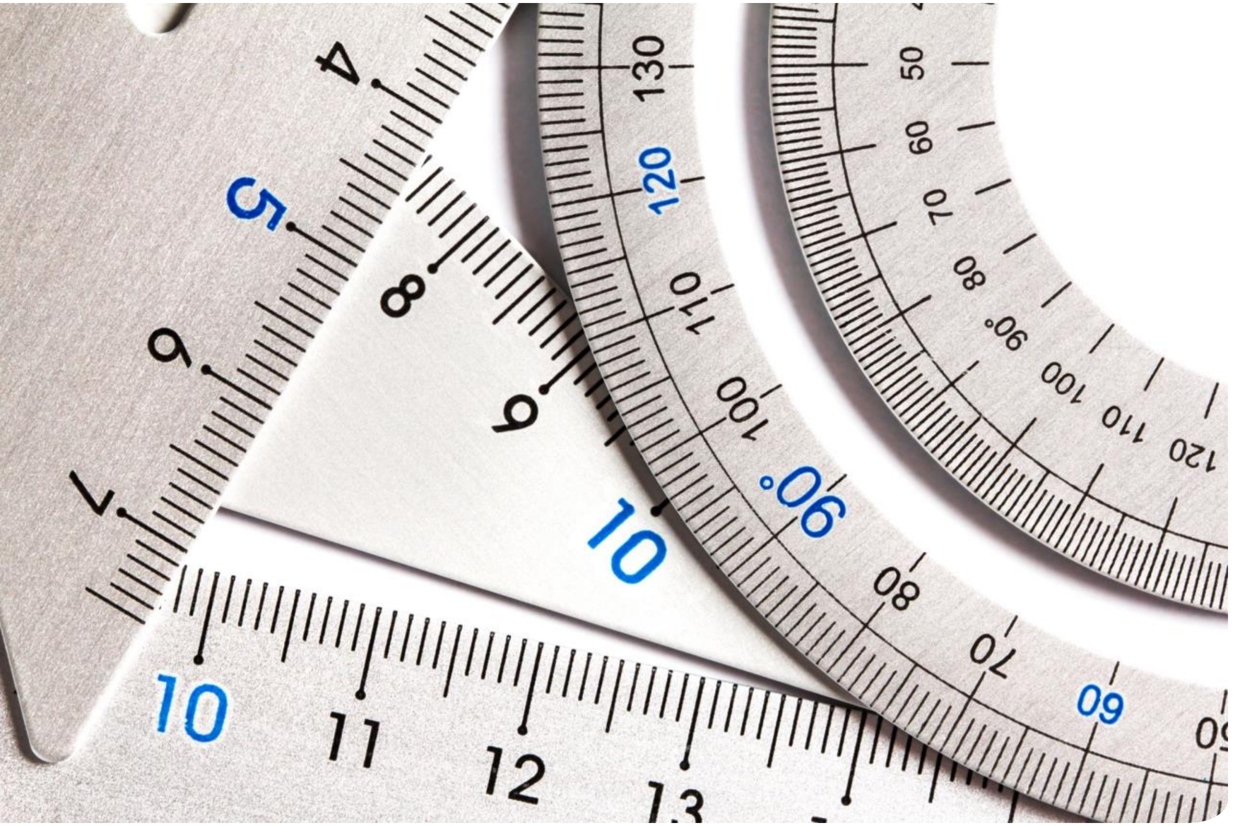


# Measurement – Direct Approaches

9/9/2024

# What does it mean to measure something?

- **Measurement**: the process of *assigning a number* to an observation. Measurement produces *quantitative* data.
  - Examples:
    - Behavioral: reaction time, performance accuracy
    - Subjective: survey response (Likert scale)
    - Neural:
      - Raw: a single-cell firing time, an EEG sample, an MRI voxel
      - Processed: an average rate of firing, an EEG feature like alpha power, an MRI connectivity map

# Signal vs Noise

- You typically have to process your data to separate the meaningful **signal** (the information you want) from the rest of the **noise** (the unwanted variation that interferes with the signal). In the context of neural data:
  - Signal – the part of the neural activity data you collected that can be meaningfully associated with the processes you are studying
  - Noise – the other neural activity you are not interested in, physiological artifacts (like movement), non-organic artifacts (like electrical interference)

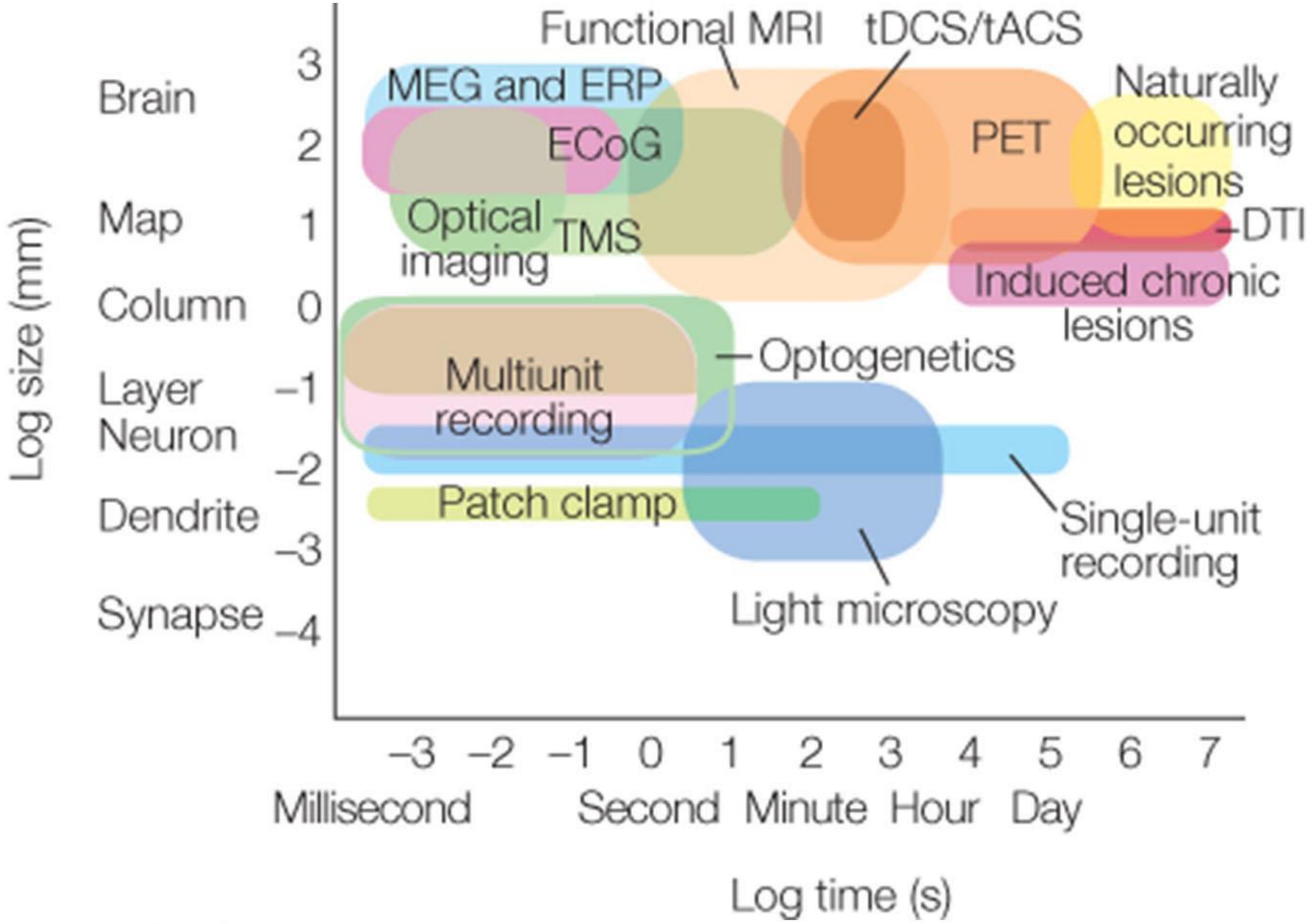
# What is noise actually?

- Noise is not just random error. It is the unwanted portion of your data that interferes with your signal.
- Physiological noise:
  - Heartbeats, breathing, blinking, jaw clenching can all create noise
  - This may be a systematic response to the stimulus you are presenting!
- Neural noise:
  - Intrinsic neural activity – ongoing activity unrelated to the task under study
  - Think about all the hidden coordination of homeostatic regulation, your background thoughts, your ongoing monitoring of your environment
- Measurement noise:
  - Imperfections in recording instruments, misalignment of MRI images, accounting for small delays in your experimental setup

Do you think randomness really exists? Or is what we call “random” just caused by the things we haven’t accounted for in our models of the world?

# What measurement tool for the brain should you use?

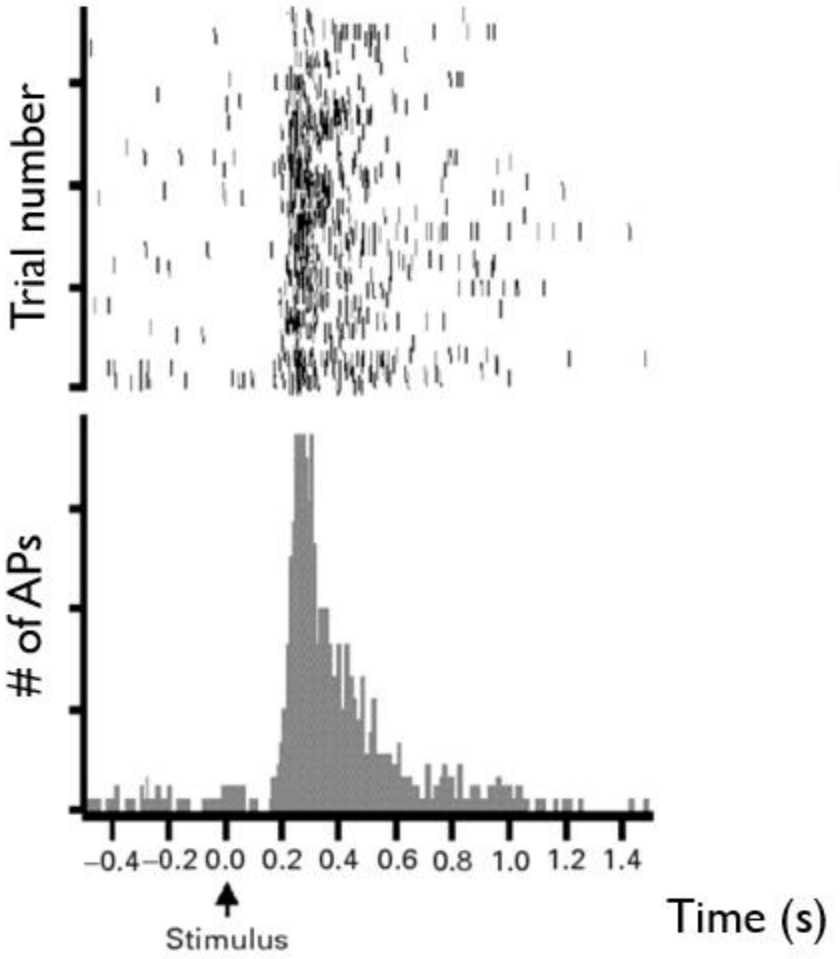
- Depends on the scale you need in space and time!
- Some methods are much more invasive than others
- Some methods on this chart are perturbative methods, and we will talk about those in the context of brain stimulation



| Method | Spatial Resolution | Temporal Resolution | Convenience | What does it measure? | Structural or Functional? | Direct or Indirect? |
|---|---|---|---|---|---|---|
| Single / multi-unit recording | High | High | Invasive (surgery) | Action potentials of individual or groups of neurons | Functional | Direct |
| EEG | Low but improving | High | Noninvasive, scalp electrodes | Electrical activity from the scalp | Functional | Direct |
| iEEG (includes ECoG) | High | High | Invasive (surgery) | Local field potentials (LFPs) | Functional | Direct |
| ERP | Low but improving | High | Noninvasive, scalp electrodes | Event-related electrical potentials (brain responses) | Functional | Direct |
| MRI | High | Low | Noninvasive, MRI machine | Tissue density and structure | Structural | Indirect |
| fMRI | High | Mid | Noninvasive, MRI machine | Blood oxygenation level-dependent (BOLD) signal | Functional | Indirect |
| DTI | High | Low | Noninvasive, MRI machine | White matter tracts | Structural | Indirect |
| PET | High | Low | Invasive (injecting tracers), PET machine | Metabolic activity using radioactive tracers | Functional | Indirect |

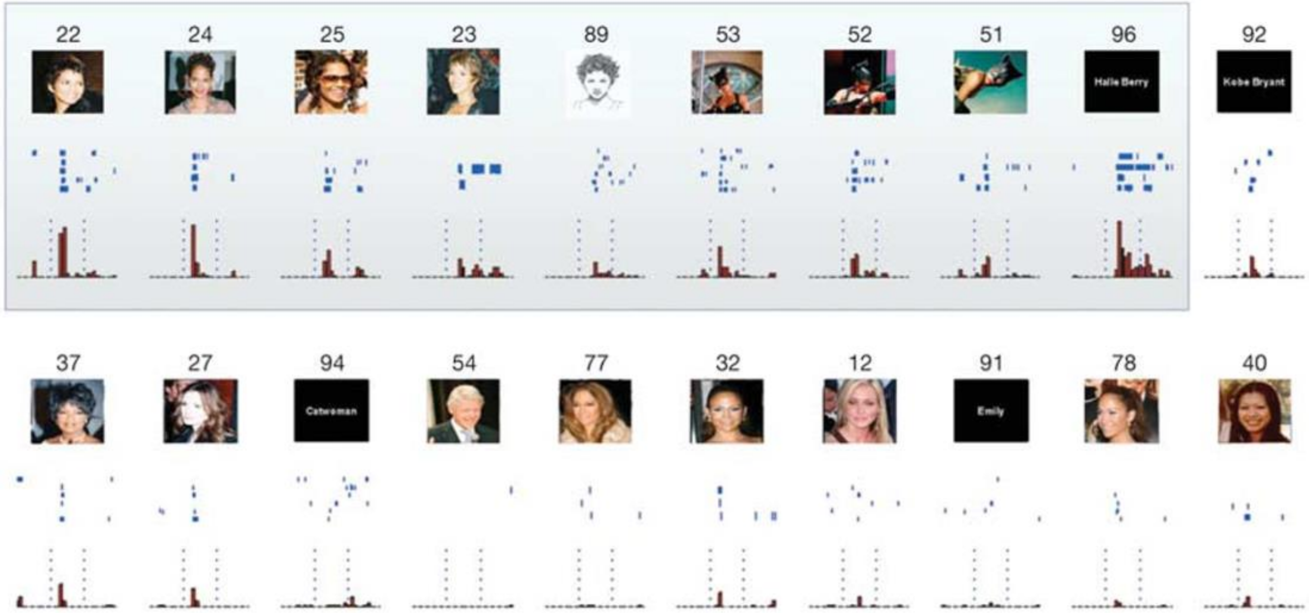
# Single/multi-unit recording

- An extremely small electrode that measures the activity of an individual neuron (single-unit) or a small group of neurons (multi-unit)
- Generates a **raster plot** (above) that marks individual action potentials with a tick across time, allowing you to estimate a neuron's average **firing rate** (histogram below)
- Provides extremely detailed data, very high spatial and temporal resolution
- Extremely invasive – requires surgery implantation – and can only be applied to small, specific parts of a brain



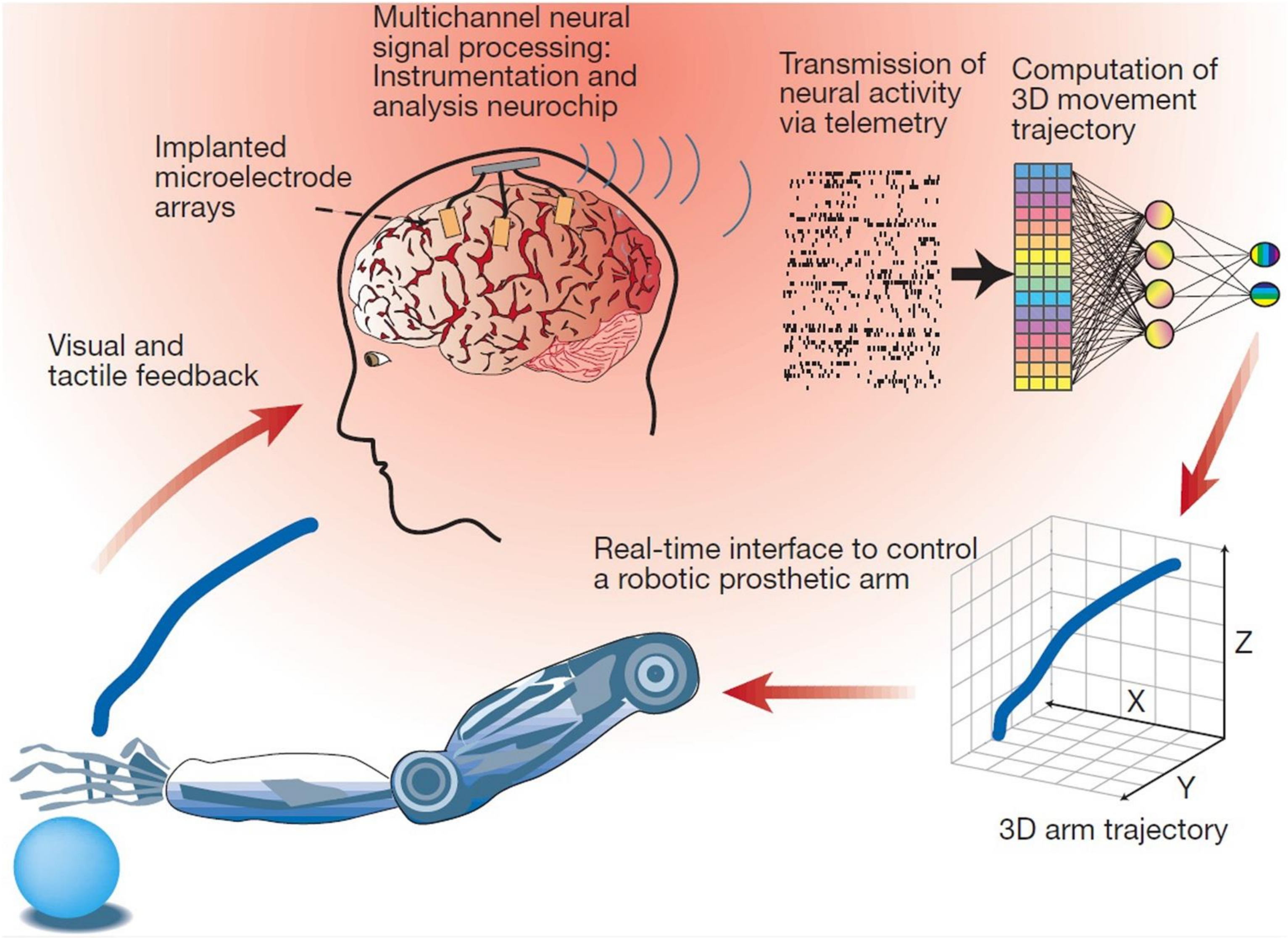
# Single/multi-unit recording

- Is there a Halle Berry neuron in this patient?
- Recordings from a single neuron in the hippocampus of an epilepsy patient within the course of a few hours/days
- **Neural drift** – the pattern of these neural activities drift with time; they are not stable to a specific neuron, posing a challenge for modern brain implant technologies



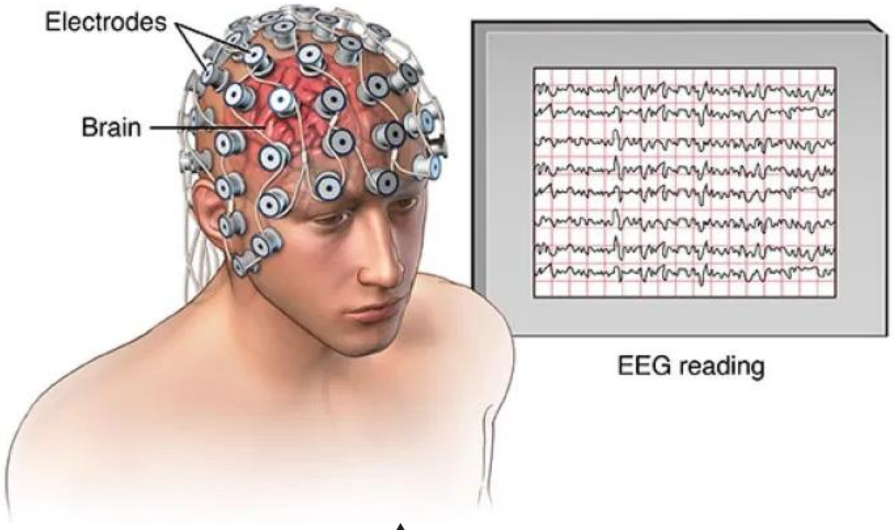
# These types of electrodes are the basis for brain implants

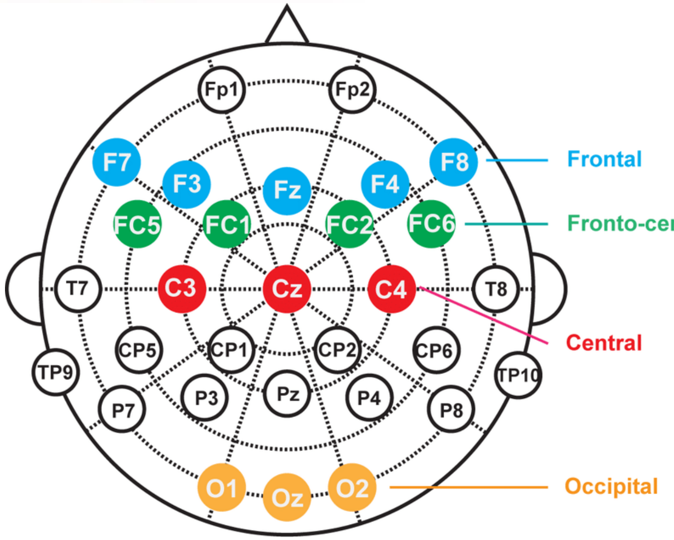
- Record high-density neural activity data from many electrodes
- Use AI to interpret those data into software commands



# Electroencephalography (EEG)

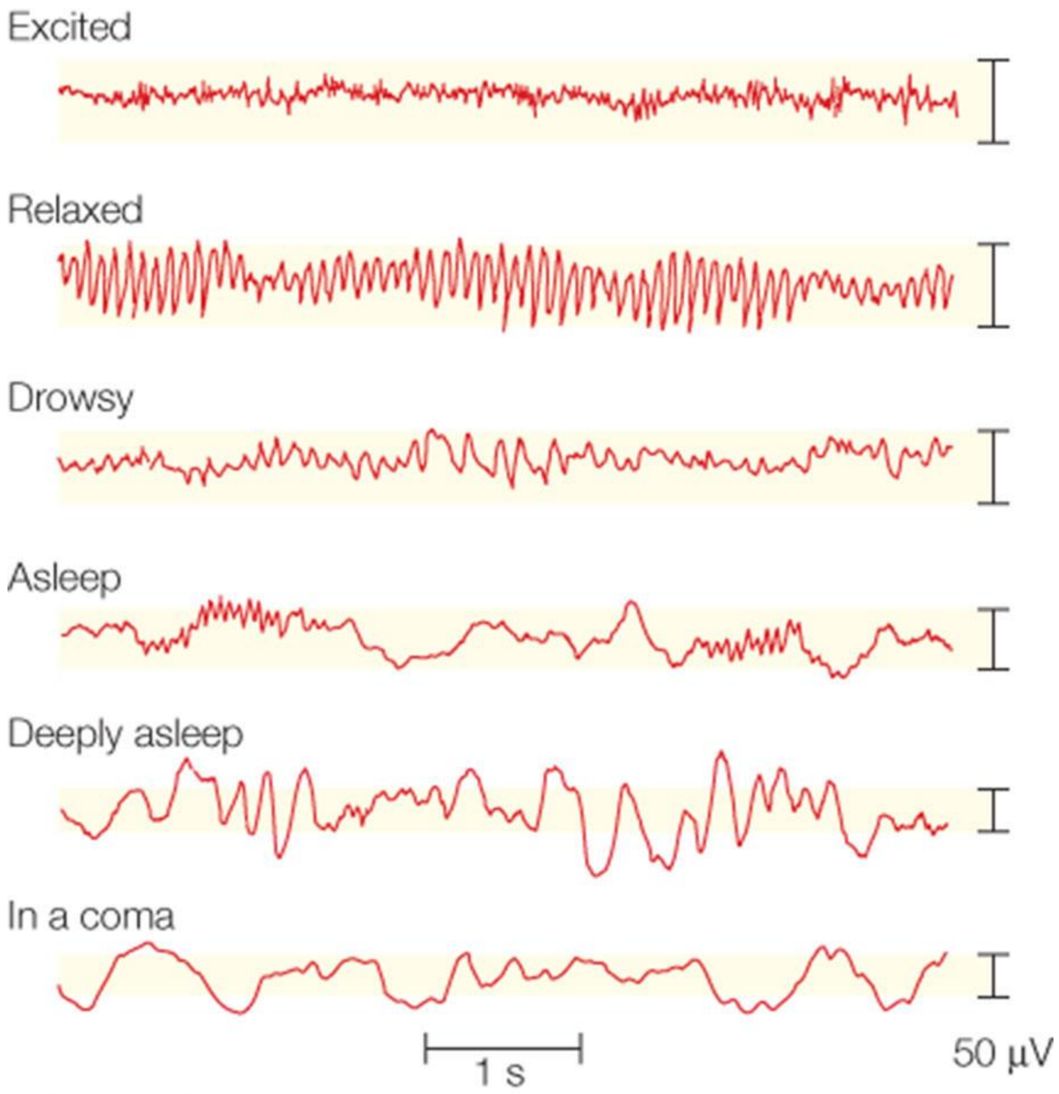
- Electrical (electro-) brain (encephalo-) recording (-graphy)
- Placing electrodes on the scalp allows for noninvasive recording of the brain’s electrical activity
- EEG signal = the integration of postsynaptic potentials (microvolts, mV) across neural populations
- Scaling problem: difficult to connect neurophysiology and neural circuitry (microscale) with the patterns seen in EEG (macroscale)



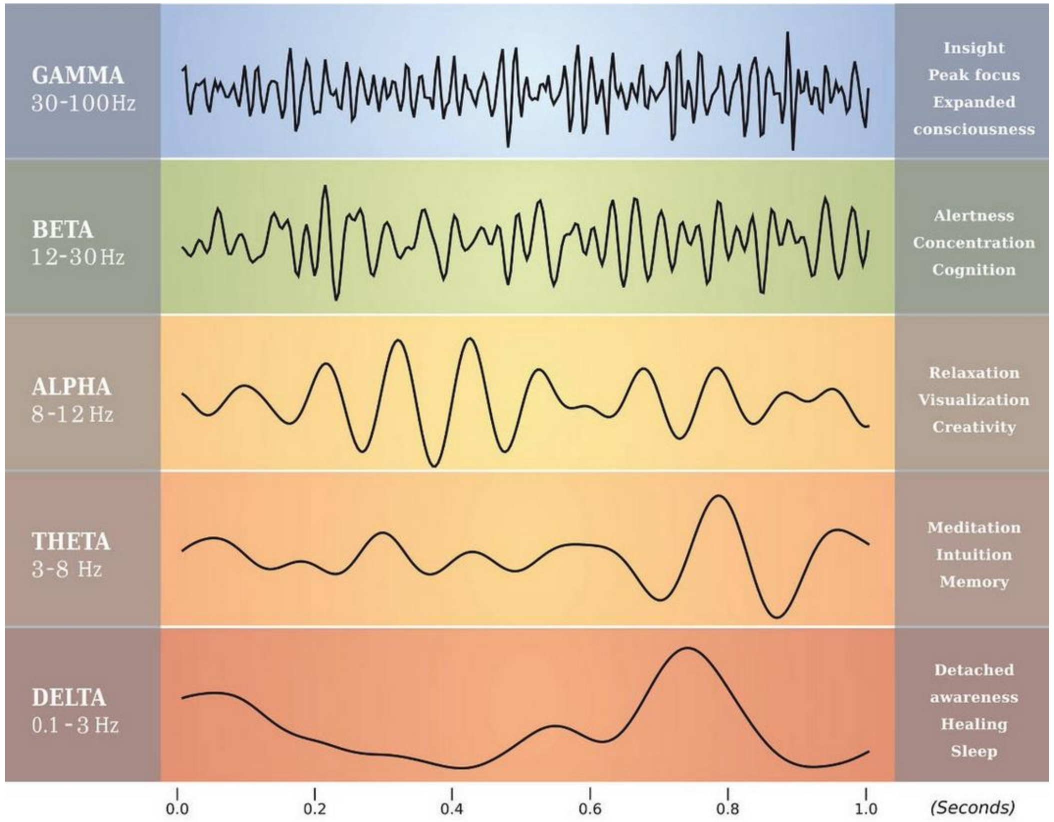
# EEG

- EEG signals can capture various states of arousal by looking at the types of oscillations occurring
- EEG can also be used to detect **epilepsy**, a condition that causes **seizures** – when large numbers of neurons uncontrollably synchronize



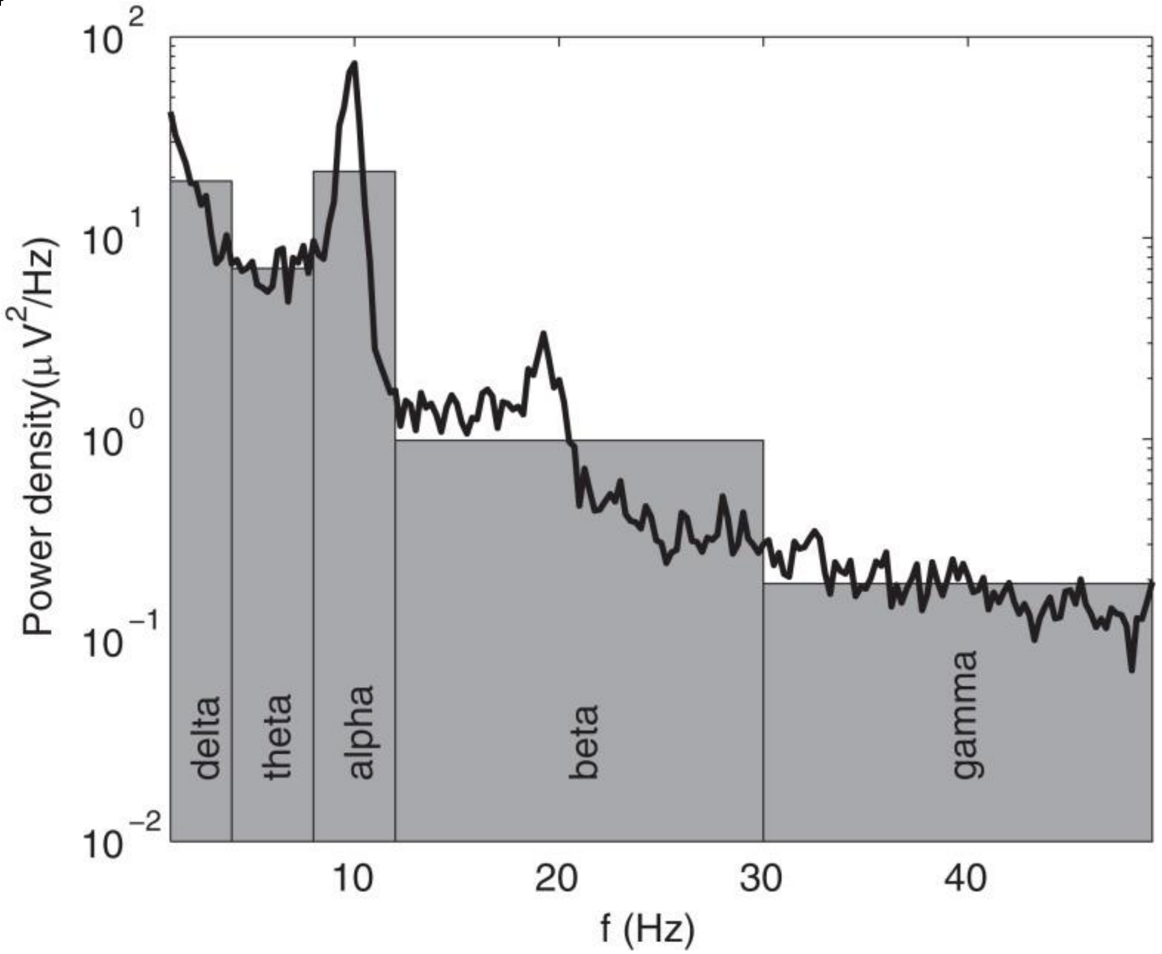
# EEG Analysis

- Look at **frequency** (how fast is it oscillating) and **power** (how large is the oscillation)
- Faster waves tend to mean more mental activity, slower waves tend to mean more relaxation, or less activity



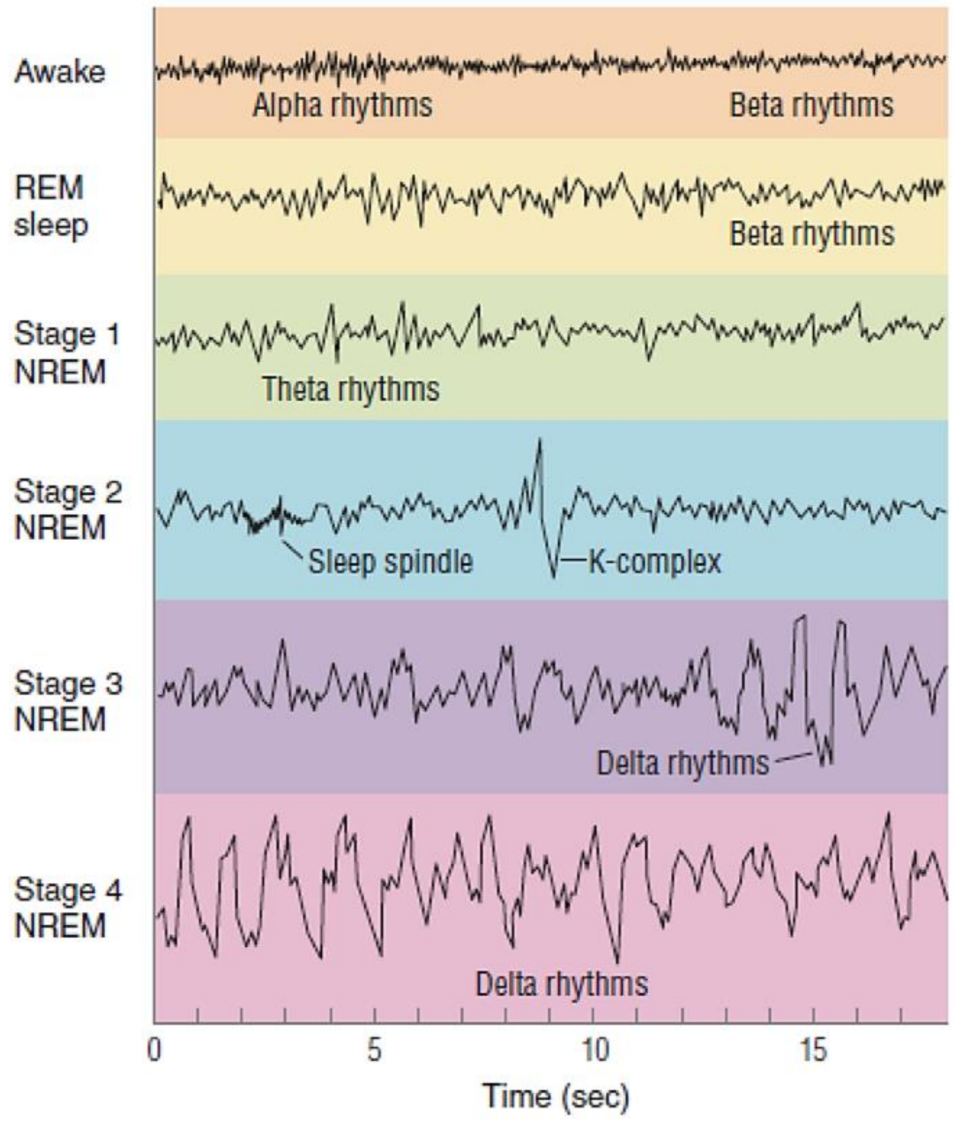
# EEG Frequency Spectrum

- Follows a 1/f pattern, known as pink noise or fractal noise
  - Slower frequencies have more power
- There is a noticeable bump in the alpha range



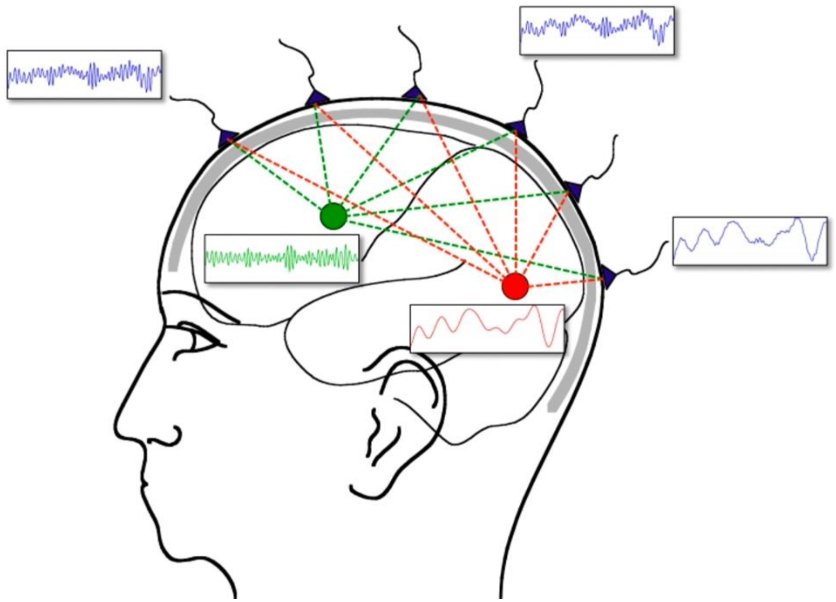
# EEG can detect sleep stages

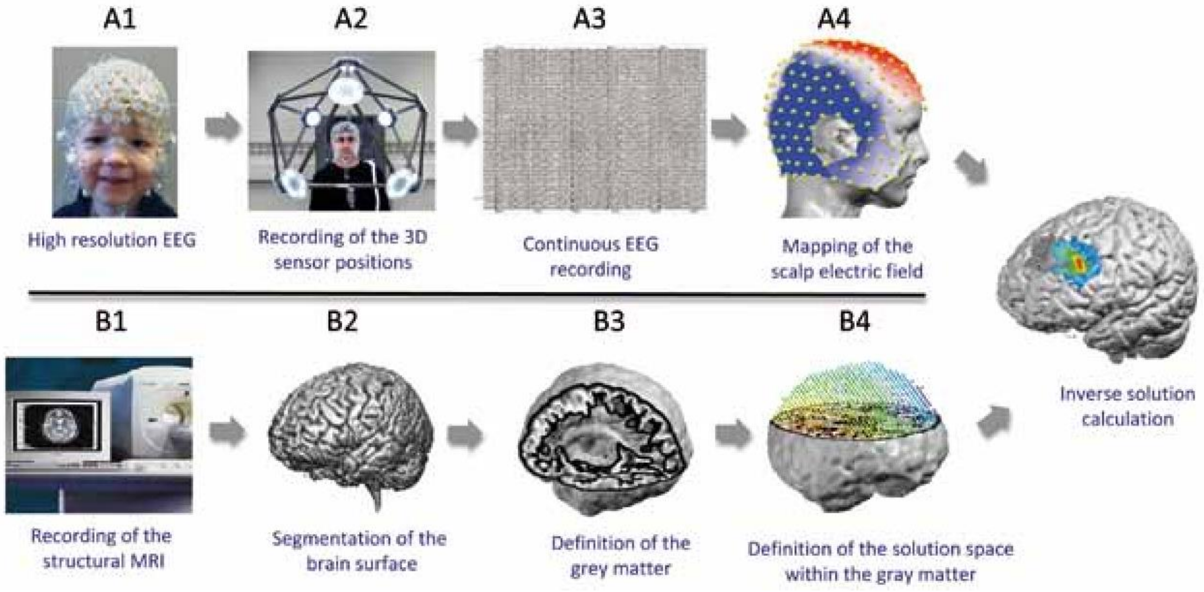
- You can identify different stages of sleep by the different patterns of brainwaves
- **REM (rapid eye movement) sleep** is when you are dreaming, and your brainwaves are much faster (beta and gamma) during this period than deep sleep (delta)



# EEG spatial accuracy

- A difficult problem in EEG analysis is **source localization** – where in the brain is this electrical activity coming from?
- The problem is that there are always multiple possible solutions
- Emerging modern methods combine data from MRI to estimate a model of the electrical field – controversial!





# QEEG: Quantitative EEG

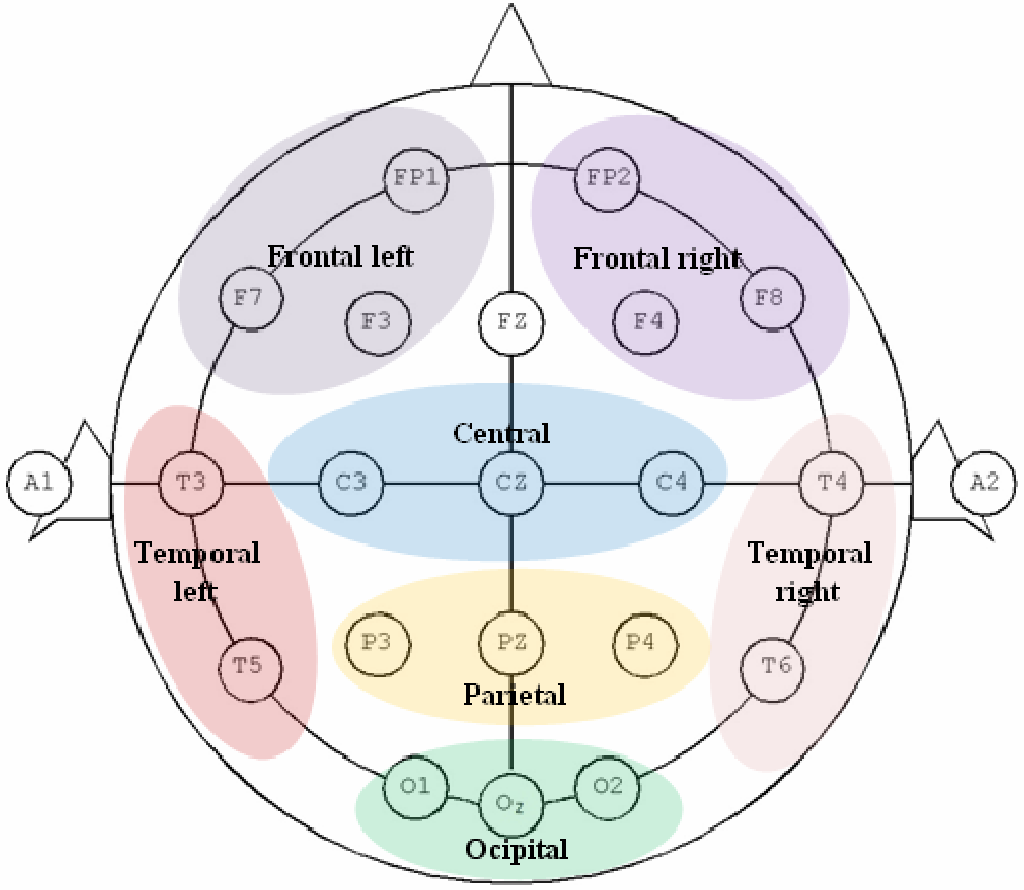
- Transforms raw EEG data into quantifiable metrics, typically displayed in brain maps
- Used to identify patterns associated with neurological or psychiatric conditions (ADHD, depression, anxiety)
- Compare a patient's brainwave patterns with a normative average
- Used with neurofeedback or brain stimulation to treat conditions

# QEEG Features

- **Absolute power**: Total power of a frequency
  - Abnormal (too high or too low) power may indicate under- or over- activity
  - Excessive theta may indicate ADHD, reduced alpha may indicate inability to relax or focus
- **Relative power**: Ratio of a frequency's power to the total power across all frequencies
  - More clearly shows imbalances in the system
  - High beta relative power in frontal lobe may indicate excessive cognitive or emotional effort
- **Coherence**: synchronization or connectivity between regions
  - High coherence may indicate rigid, over-connected networks (may see in OCD)
  - Low coherence may indicate brain communication difficulties (may see in injury or learning disabilities)
- **Asymmetry**: difference in power between hemispheres
  - Often focuses on alpha frequency
  - Left-frontal alpha asymmetry is often seen in depression
- **Peak alpha frequency**: the peak frequency of alpha oscillations
  - Slower alpha peak associated with cognitive decline or fatigue
  - Higher peak associated with sharper/faster mental processing
- **Beta/theta ratio**: ratio of beta power to theta power
  - Higher ratio linked with heightened cognitive focus or stress
  - Lower ratio may suggest inattention or impulsivity (may see in ADHD)

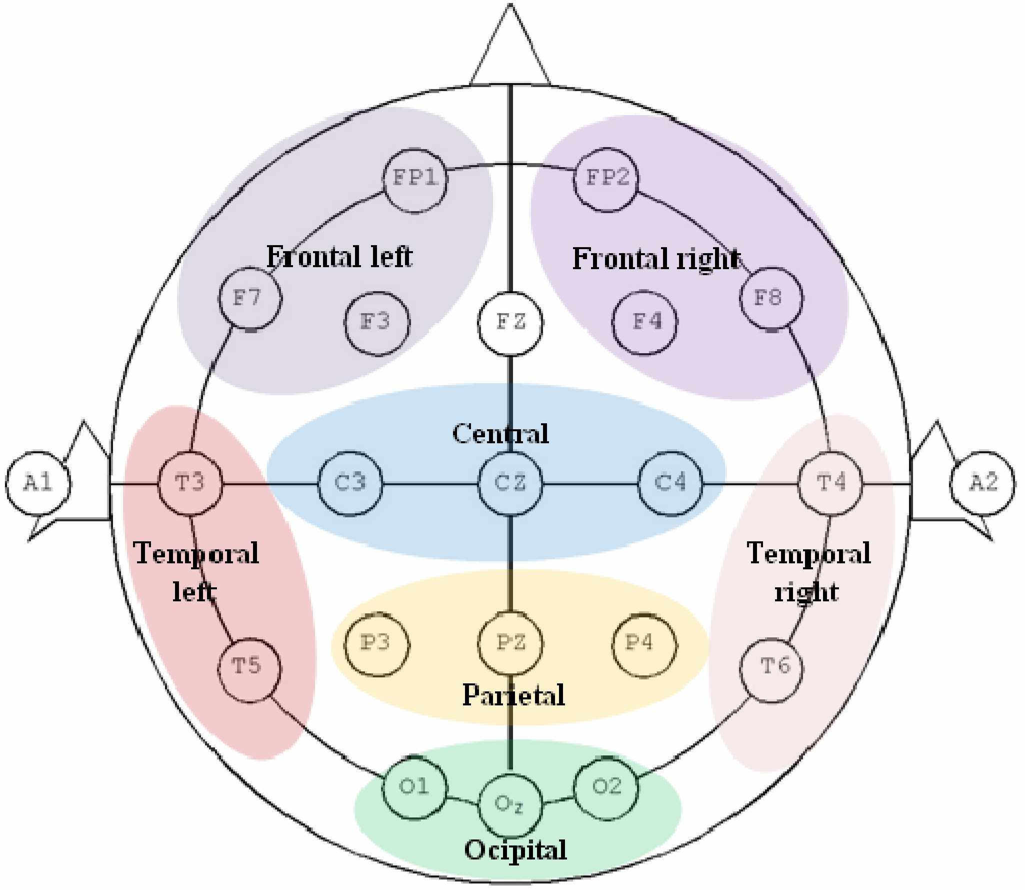
# QEEG Locations

- **Frontal Lobes** (F3, F4, F7, F8): executive function, decision-making, attention, impulse control, emotional regulation
  - **Excess beta** associated with anxiety, stress, hypervigilance
  - **Low alpha** or **high theta** may indicate attention deficits, ADHD, poor focus
  - **Frontal alpha asymmetry** linked to mood disorders
- **Prefrontal Cortex** (Fp1, Fp2): planning, decision-making, personality expression, moderating social behavior
  - **Excess beta** associated with overthinking, worry, rumination, common in anxiety
  - **Low beta** or **high theta** linked to poor executive functioning, low motivation, or anhedonia, often seen in depression and other mood disorders
- **Central/Motor Cortex** (Cz, C3, C4): motor control, sensorimotor processing, coordination
  - **Excess beta** associated with muscle tension, motor restlessness, disorders like Tourette's or anxiety
  - **Low beta** can indicate poor motor coordination or sluggishness, often seen in motor developmental delays or some forms of ADHD



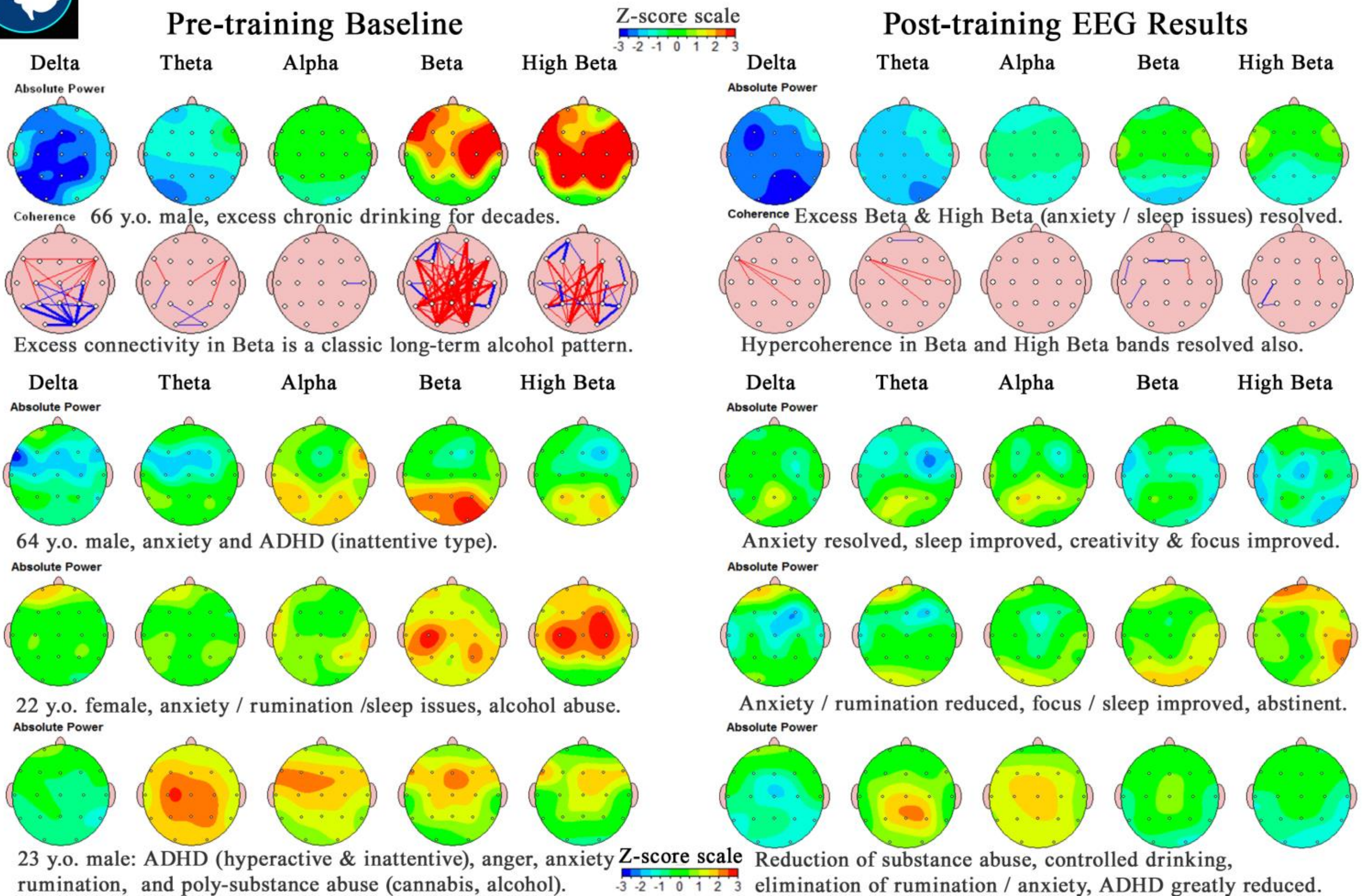
# QEEG Locations

- **Temporal Lobes** (T3, T4, T5, T6): memory, auditory processing, language, emotional response/regulation
  - **Excess slow-wave (delta and theta)** associated with emotional dysregulation, irritability, or possible epilepsy
  - **High beta** associated with emotional dysregulation, especially in context of anxiety/mood disorders
  - **Asymmetry** often seen in speech or language problems (dyslexia, aphasia)
- **Parietal Lobes** (Pz, P3, P4): Sensory processing, spatial awareness, visuomotor integration, perception
  - **Excess theta or delta** associated with learning difficulties, poor processing of sensory information, slow cognitive processing
  - **Low alpha** associated with difficulty in shifting attention or problems in sensory integration, often seen in ADHD or learning disabilities
- **Occipital Lobes** (Oz, O1, O2): visual processing, perception of movement, color recognition
  - **Excess slow-wave (delta and theta)** associated with visual processing problems or cognitive decline
  - **Excess alpha** may indicate relaxation or disengagement, but may also indicate issues with visual attention if the person is trying to engage



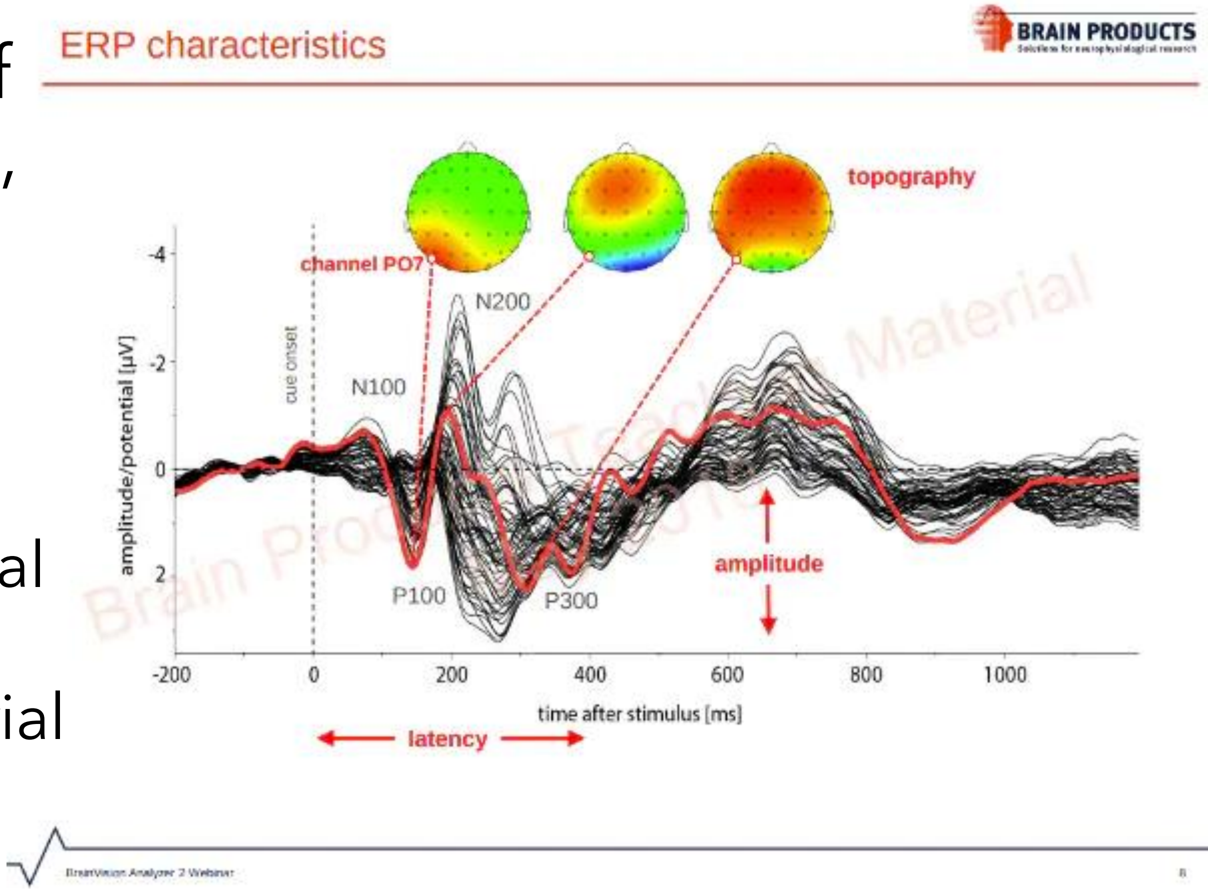
Peak Brain Institute

QEEG Z-scored “Brain Maps” Pre- and Post-Neurofeedback (avg 30 sessions).



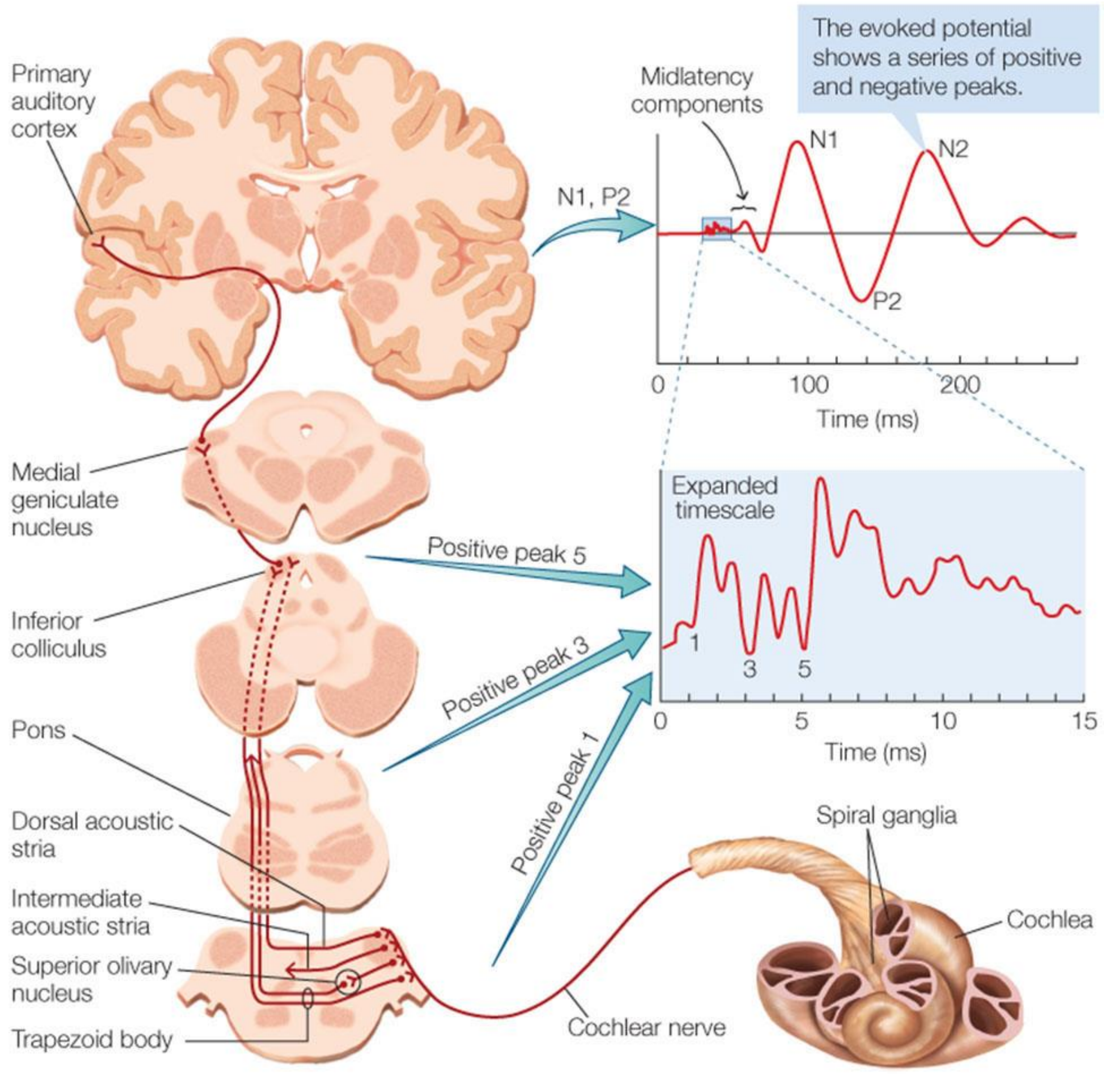
# Event-Related Potential (ERP)

- If you perform a trial hundreds of times (like presenting a stimulus), you can average all those trials together **timelocked** to the stimulus, and you can extract a signal from the noise
  - The activity that is different each trial (the noise) will average to zero
  - The activity that is the same each trial (the signal) will remain



# ERP analysis

- Peaks (**P**=positive) and valleys (**N**=negative) are numbered by the **latency** (time) at which they reach their apex
  - Sometimes this marks the order (N1, P2), or it marks the specific time in milliseconds (P300)
  - The **amplitude** (in either direction) and the **latency** of the different ERPs are what matter
- These events can signify stages of neural processing



# EEG

**Pros**

- Non-invasive
- High temporal resolution
- Inexpensive, portable
- Rich history of use in research and diagnostics

**Cons**

- Low (but improving!) spatial resolution
- Not ideal for estimating subcortical activity
- Susceptible to artifacts
  - Skull blocks signal, muscle noise, environmental noise
- Can be difficult to interpret
  - Alpha waves? So what?

# Intracranial EEG (iEEG)

- You can surgically implant an array of electrodes inside the brain and record very high-quality data this way
  - If you do it just on the outer cortex, this is also known as Electro-Cortiocography (ECoG)
- Gives you high spatial resolution, allowing you to estimate where a seizure may be localized
- Researchers often recruit epilepsy patients who have an iEEG array implanted to perform in their experiments