Week 1: EEG Signal Processing Basics

Gabor Stefanics (TNU)

EEG Signal Processing: Theory and practice
(Computational Psychiatry Seminar: Spring 2015)
Outline

- Physiological bases of EEG
- Amplifier basics
  - Usual EEG lab components
  - Basic acquisition, Electrode placement
  - How EEG Travels From the Brain to the Recording Device
  - Measurement Issues
  - Why is Electrode Gel Necessary?
  - Why is the Amplifier Necessary, and What Does it Do?
  - Why is the Amplifier Input Impedance Important?

- Signal processing basics
  - What Is Cognitive Electrophysiology?
  - Why EEG? Why Not EEG?
  - Interpreting Voltage Values from the EEG Signal
  - Temporal and Spatial Resolution, Precision, and Accuracy of EEG
  - EEG Time-Frequency: The Basics
  - Preprocessing and Artifacts: Their Detection, Influence, and Removal
  - Overview of Time-Domain EEG Analyses
  - Practicalities of EEG Measurement and Experiment Design
  - Tips for Data Collection
1) When an Action Potential reaches the axon terminal the neuron releases a neurotransmitter.

2) The neurotransmitter binds to the receptor.

3) The postsynaptic neuron gets depolarized (Na\(^+\) inward currents – excitatory - EPSP) or hyperpolarized (Cl\(^-\) inward currents – inhibitory - IPSP).

4) EPSP and IPSP summate temporally and spatially.

5) If the postsynaptic neuron reaches a given depolarization threshold, an action potential is generated.
When an EPSP is generated in the dendrites of a neuron, an extracellular electrode detects a negative voltage difference, resulting from Na\(^+\) currents flowing inside the neuron’s cytoplasm.

The current completes a loop further away the excitatory input (Na\(^+\) flows outside the cell), being recorded as a positive voltage difference by an extracellular electrode.

This process can last hundreds of milliseconds.

Thus, a small dipole is generated!!

Extracellular fields arise because the slow EPSPs and IPSPs allow for the temporal summation of currents of relatively synchronously activated neurons.
Dipoles
Open and closed fields

Radial dipole
Tangential dipole

Open field
Closed field

Jackson and Bolger (2014) Psychophysiology

Cohen (2014) MIT Press
Scalp EEG cannot determine if activity is excitatory or inhibitory

EPSP (producing an extracellular negativity) at the apical dendrites

IPSP (producing an extracellular positivity) near the soma

Either of these signals will be measured as a negative deflection in the EEG

EPSP (producing an extracellular negativity) near the soma

IPSP (producing an extracellular positivity) at the apical dendrites

Either of these signals will be measured as a positive deflection in the EEG

Jackson and Bolger (2014) Psychophysiology
- Amplifier basics
  - Usual EEG lab components
  - Basic acquisition, Electrode placement
  - How EEG Travels From the Brain to the Recording Device
  - Measurement Issues
  - Why is Electrode Gel Necessary?
  - Why is the Amplifier Necessary, and What Does it Do?
  - Why is the Amplifier Input Impedance Important?
Usual EEG lab components

Subject stimulus screen and headphone

Behavioral responses

Stimulus

Stimulus PC

Experiment event markers

EEG data

QuickAmp amplifier

EEG recording PC

USB box

PC

PC
- Signals on the scalp are very small – microvolt range (1/1’000’000 volts).

- Presents some challenges for acquisition

- Acquisition involves
  - Amplification
  - Filtering
  - Digitizing
  - Storage

- Results in one time series per channel (up to 128 at the TNU).
- EEG signals are a measure of **potential difference between two electrodes**.

- Just like the voltage at a battery is the difference between positive and negative poles.

- Thus you always need at least 2 recording electrodes to get a signal.

- In practice we use many electrodes but each EEG signal is always the difference between the signal from 2 or more electrodes.
Electrode placement

Traditional 10-20 or 10-10 layouts

Equidistant layouts
EEG time series
From Brain to Electrode

Why is Electrode Gel Necessary?

The capacitor stack with electrode gel, showing the neural signal propagating through layers of brain, dura, skull, and electrode gel to reach the electrode. Because the gel is a conductor, the signal reaches the electrode with less attenuation than if the gel were not present.

Jackson and Bolger (2014) Psychophysiology

The capacitor stack with no electrode gel. Note that the layer composed of hair and air is an insulator rather than a conductor, so the signal is attenuated when measured at the electrode.
Why is the Amplifier Input Impedance Important?

Voltage drop across resistance

Each resistor in the circuit will produce a *voltage drop proportional to the total resistance*.

Here, if both resistors are 100 ohms, then each resistor represents half of the total resistance, so each resistor would drop half of the voltage.

Calculating voltage drops across resistance.

If one of the resistors here has a resistance of 100 ohms and the other has a resistance of 1,000 ohms, then the former is 100/1,100 of the total resistance, and so drops 100/1,100 of the total voltage.

Jackson and Bolger (2014) Psychophysiology
Noise entering the EEG measurement system

Say the input impedance is 100 ohms:
Signal: 100 ohms of resistance from the wire, 100 ohms from the amplifier. The ratio of amplifier resistance to total resistance is 100/(100 + 100) = .5. This results in a voltage drop across the input impedance of the amplifier that is 50% of the signal’s voltage.
Noise: 5 ohms of resistance from the wire, 100 ohms from the amplifier. Ratio of amplifier resistance to total resistance is 100/ (100 + 5) = .9524. This results in a voltage drop across the input impedance of the amplifier that is 95.24% of the noise’s voltage.

Say the input impedance is 1 million ohms:
Signal: 100 ohms of resistance from the wire, 1,000,000 ohms of resistance from the amplifier. Ratio of amplifier resistance to total resistance is 1,000,000/1,000,100. This results in a voltage drop across the input impedance of the amplifier that is 99.990% of the signal’s voltage.
Noise: 50 ohms of resistance from the wire, 1,000,000 ohms of resistance from the amp. Ratio of amplifier resistance to total resistance is 1,000,000/1,000,050. This results in a voltage drop across the input impedance of the amplifier that is 99.995% of the noise’s voltage.
Input impedance of two amplifier systems

BrainAmp DC
Input impedance: 10000 MOhm

Biosemi ActiveTwo
Input impedance: 300 MOhm
Why is it important to minimize resistance between electrode and scalp?

Of all the connections in an EEG system, the connection between electrode and scalp is the most relevant for day-to-day usage.

The signal is passed along at the scalp, but measured at the amplifier. A smaller resistance allows more signal to pass through, because it drops less voltage, leaving more voltage to continue through the circuit. A very large resistance is what allows the voltage to be measured, because it drops as much voltage as possible, and that voltage drop is what is measured.

An EEG system should minimize the resistance across the scalp-electrode interface in order to minimize the voltage drop at that interface, so as much voltage as possible remains to be measured at the amplifier.

If the amplifier’s input impedance is much larger than the scalp-electrode resistance, then even a fairly high scalp-electrode resistance will still represent a very small portion of the total resistance. Thus, the higher the input impedance, the larger the electrode impedance that can be tolerated without losing signal quality.

Jackson and Bolger (2014) Psychophysiology
Signal processing basics

- What Is Cognitive Electrophysiology?
- Why EEG? Why Not EEG?
- Interpreting Voltage Values from the EEG Signal
- Temporal and Spatial Resolution, Precision, and Accuracy of EEG
- EEG Time-Frequency: The Basics
- Preprocessing and Artifacts: Their Detection, Influence, and Removal
- Overview of Time-Domain EEG Analyses
- Practicalities of EEG Measurement and Experiment Design
- Tips for Data Collection
What Is Cognitive Electrophysiology?

How cognitive functions are supported or implemented by the electrical activity produced by populations of neurons.

Cognitive Electrophysiology: The Art of Finding Anthills on Mountains
EEG signals are noisy, findings are sometimes hidden in dimensions that are difficult to visualize without filters or other data transformations, results can be infected with artifacts or may be statistical false alarms, and interpretations are usually based on probabilities, inferences, and speculations. **Good science** — in addition to being based on theory, previous research, careful experiment design, and appropriate data analyses and statistics — is also about discovering and appreciating subtlety. And the appreciation of subtlety becomes more important with time as basic findings become established fact. This is good; it reflects progress. Discovering subtleties involves considering theories, previous research, and openness to letting the data “speak for themselves.”

Cohen (2014) MIT Press
Why EEG?

1) **High-temporal-resolution**: capture cognitive dynamics in the time frame in which cognition occurs. Cognitive, perceptual, linguistic, emotional, and motor processes are fast. Most cognitive processes occur within tens to hundreds of milliseconds.

2) EEG directly **measures neural activity**. The neurophysiological mechanisms that give rise to population-level oscillations are well understood and can be modeled fairly accurately.

3) EEG data comprise **at least four dimensions**: time, space, frequency, and power (the strength of frequency-band-specific activity) and phase (the timing of the activity); power and phase are distinct attributes because they provide largely independent information. This multidimensionality provides **many possibilities for specifying and testing hypotheses** that are rooted both in neurophysiology and in psychology.

Why Not EEG?

1) EEG is **not well suited for studies in which precise functional localization is important**, and EEG is not well suited for testing hypotheses about deep brain structures.

2) Another set of research questions for which EEG may be a suboptimal brain-imaging technique includes those **questions concerning cognitive processes that are slow and that have an uncertain and variable time course**.

Cohen (2014) MIT Press
Microvolt values can be difficult to interpret in an absolute sense, because

1) microvolt values will change depending on data processing and analysis decisions, including the choice of reference and the time period used for baseline subtraction;

2) raw voltage values can be difficult to interpret as microvolt values differ across subjects according to irrelevant factors such as skull shape and thickness, scalp preparation during the recording, the orientation of the dipole in the brain that generated the scalp-measured activity, cortical folding, whether the subject washed his or her head that morning, and other factors. These are not global factors, meaning that there can be local differences in voltage values across the head. The voltage value might also be influenced by the quality of the EEG electrodes and amplifier as well as by built-in hardware filters.

Cohen (2014) MIT Press
1) **Resolution** refers to the number of data samples per unit time (the number of dots),

![ERP from electrode Pz](image)

2) **Precision** refers to the certainty of the measurement at each time point (depends on the analysis, e.g. convolution),

3) and **accuracy** refers to the relationship between the timing of the EEG signal and the timing of the biophysical events that lead to the EEG signal.

Cohen (2014) MIT Press
1) Spatial resolution: determined by the number of electrodes. The spatial resolution that you need depends on the kinds of analyses you will perform.

2) The spatial precision of EEG is fairly low but can be improved by spatial filters such as the surface Laplacian or adaptive source-space-imaging techniques. Simulation studies show that with many electrodes (> 200) and anatomically precise forward models of subject-specific brain and skull anatomy, the spatial precision of source reconstruction can be fairly high.

3) The spatial accuracy of EEG is low. Activity recorded from one electrode does not reflect only activity from neurons directly below that electrode, but rather, from a complex mixture of activities from many brain regions close to and distant from that electrode.

Cohen (2014) MIT Press

Scalp electroencephalographic (EEG) electrodes record sums of activity from cortical sources and non-brain processes, making direct interpretation of scalp channel waveforms problematic. As an example, this silent 1/5th-speed simulation by Zeynep Akalin Acar and Scott Makeig shows (on the left) two cm-sized, parietal EEG sources expressing simulated alpha band activities (at 9 Hz and 10 Hz respectively), and (on the right) their summed scalp projection. Note the strong difference between the cortical source dynamics (left) and scalp EEG dynamics (right), and the difficulty of determining the nature and locations of the source activities directly from the scalp pattern. http://sccn.ucsd.edu/eeglab/
1) **Designing Experiments**: Discuss, Pilot, Discuss, Pilot.

2) **Event Markers**: are critical because they are used to time-lock the EEG data offline. They are also used to reconstruct different conditions and responses. Therefore, it is better to have markers encode too much rather than too little information.

3) **Intra- and Inter-trial Timing**: allow the brain response to one event to subside before the response to the next event begins. Consider carefully what period of time you will use for baseline normalization of task-related data and what frequencies you want to analyze.

4) **How Many Trials You Will Need**: depends on the signal-to-noise characteristics of the data (that is, how clean vs. how noisy the data are), how big the effect is, and the type of analysis you will perform. There is no magic number of trials that will guarantee good results.

Cohen (2014) MIT Press
5) Which **Sampling Rate** to Use: you need to sample at least twice the highest frequency of interest. (**Nyquist theorem: only frequencies below half the sampling rate can be recovered.**)

Cohen (2014) MIT Press

Aliasing is well known in temporal digitization. The signal on the left has (almost) enough digital samples to reconstruct the primary frequency. The signal on the right has too few digital samples, so that the digitized signal is “aliased,” meaning that it appears to be lower frequency than it is.

Digitization (or discretization) is the same in space as in time. With too few EEG channels, the surface potentials may appear to be of lower spatial frequency (i.e., smooth), so investigators assume they don’t need more channels.
6) **How Many Electrodes**

You Will Need: depends on what analyses you plan on performing and what inferences you plan on drawing.

---

**Sampling of two examples of spatial frequency with 129-, 64-, 32-, and 19-channel sensor arrays.**

The top row shows four cycles of azimuth and four cycles of elevation. Acceptable accuracy is shown for the 32-channel array, but not for the 19-channel array. The bottom row shows four cycles of azimuth and seven of elevation. Only the 129-channel array provides accurate sampling.

- If the brain’s potentials produce very large dipolar fields (as large as one quadrant of the brain), then 64 channels is adequate, and 32 is probably close enough.
- If the fields are smaller, e.g., the size of half of a lobe synchronously active, then even 64 channel sampling is inadequate, and aliasing occurs.

Advantages of Event-Related Potentials

1) **ERPs are simple and fast to compute** and require few analysis assumptions or parameters. If the point of your experiment is to test whether brain processing is different between two conditions, and you have no preconceptions about what kinds of electrophysiological dynamics those differences might reflect, comparing ERPs across the two conditions is the fastest and easiest approach to address this question.

2) **High temporal precision and accuracy.** Because ERPs generally involve very little data processing and gentle or no temporal filters, the estimate of electrical activity at each millisecond is very precise.

3) There is an **extensive and decades-long literature** of ERP findings in which to contextualize and interpret your results. Furthermore, this literature and the theories that have been developed around ERP findings provide ample opportunities to generate new and testable hypotheses.

4) Because ERPs are fast to compute and easy to look at, they provide a **quick and useful data quality check** of single-subject data.

Cohen (2014) MIT Press
Limitations of ERPs

1) ERPs reveal relatively little of the information present in EEG data. In other words there are many kinds of dynamics in EEG data that do not have a representation in the ERP.

2) ERPs provide limited opportunities for linking results to physiological mechanisms. This is because the neurophysiological mechanisms that produce ERPs are less well understood compared to the neurophysiological mechanisms that produce oscillations.
Advantages of Time-Frequency-Based Approaches

1) Many results from time-frequency-based analyses can be interpreted in terms of neurophysiological mechanisms of neural oscillations. Oscillations are ubiquitous and fundamental neural mechanism that supports myriad aspects of synaptic, cellular, and systems-level brain function across multiple spatial and temporal scales.

2) Oscillations are arguably the most promising bridge that links findings from multiple disciplines within neuroscience and across multiple species.

3) If you accept that EEG data capture a dynamic and multidimensional space of brain processing, then ERPs reveal a fraction of that space, and time-frequency-based analyses reveal more (although not all) of that space. Thus, there may be many task-relevant dynamics in EEG data that are retrievable using only time-frequency-based approaches.

Limitations of Time-Frequency-Based Approaches

1) Decrease of temporal precision.

2) The large number of analyses that can be applied to EEG data, and the seeming complexity of those analyses, can be intimidating. New-comers to the field may feel overwhelmed.

3) Relatively small literature on linking time-frequency dynamics to cognitive processes compared to the literature linking ERPs to cognitive processes.

Cohen (2014) MIT Press
EEG data contain rhythmic activity

-Even in raw, unfiltered, unprocessed data you can see rhythmic activity. This **rhythmic activity reflects neural oscillations, which are fluctuations in the excitability of populations of neurons**. Some oscillations are fast, some are slower, and some are very slow.

-Oscillations are described by three pieces of information: **frequency, power, and phase**

Cohen (2014) MIT Press

Ulhaas and Singer (2010)
Oscillatory Patterns of Sleep

The brain is busy at night

**Figure 7.3.** Sleep is a dampened oscillation with approximately 90-minute periods. Top: Hypnogram of a night’s sleep in a young adult human. Note periodic ascending and descending phases. Bottom: Representative scalp-recorded EEG segments from each sleep stage. EEG traces are courtesy of A.A. Borbely.
-Imagine time-frequency results as a three-dimensional (3-D) cube
Things to Be Suspicious of When Viewing Time-Frequency Results

Do Results in Time-Frequency Plots Mean That There Were Neural Oscillations?

The real answer is “It is difficult to know for sure.” On the one hand, EEG measures summed field potentials of populations of neurons, which are strongly oscillatory. Thus, meso- and macroscopic neural processes that generate oscillations will dominate EEG measurements. On the other hand, Fourier’s theorem specifies that any signal can be represented using sine waves, and thus, even non-oscillatory signals have a representation in a time-frequency plot.

Cohen (2014) MIT Press
### Phase-Locked, Time-Locked, Task-Related Activity

<table>
<thead>
<tr>
<th></th>
<th>Time-locked</th>
<th>Non-time-locked</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Non-phase-locked</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single trials</td>
<td><img src="image1.png" alt="Waveform" /></td>
<td><img src="image2.png" alt="Waveform" /></td>
</tr>
<tr>
<td>Trial average</td>
<td><img src="image3.png" alt="Waveform" /></td>
<td><img src="image4.png" alt="Waveform" /></td>
</tr>
<tr>
<td><strong>Phase-locked</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single trials</td>
<td><img src="image5.png" alt="Waveform" /></td>
<td><img src="image6.png" alt="Waveform" /></td>
</tr>
<tr>
<td>Trial average</td>
<td><img src="image7.png" alt="Waveform" /></td>
<td><strong>Undefined</strong></td>
</tr>
<tr>
<td>TF Power</td>
<td><img src="image8.png" alt="Waveform" /></td>
<td><img src="image9.png" alt="Waveform" /></td>
</tr>
</tbody>
</table>

Cohen (2014) MIT Press

**Time-locked** <-> **Induced (jittering)**
There is less empirical and theoretical work on the neurophysiological mechanisms that produce ERPs — that is, why there are positive and negative polarity peaks after experiment events.

Additive model

Phase-reset model

Amplitude asymmetry or baseline shift

Complex additive and nonlinear effects


Sauseng et al. (2007) Neuroscience 146, 1435–1444

David et al. (2006) Neuroimage
- Preprocessing: any transformations or reorganizations that occur between collecting the data and analyzing the data.

Different preprocessing strategies lead to different balances between the \textbf{amount of noise versus signal} that is retained in data. At one extreme (dashed vertical line a), the data contain nearly no noise, but this comes at the expense of losing signal. At the other extreme (dashed vertical line c), nearly all of the signal in the data is retained, but this comes at the expense of keeping noise in the data as well.

There is no optimal position to take in this theoretical function; it depends on the kinds of analyses you are performing, how many trials you have, and how tolerant your analyses are to noise.
There is no data analysis substitute for clean data.

The fanciest and most sophisticated data analyses will give you bad results if you start with bad data. On the other hand, if you have very clean and high – signal-to-noise data, even modest analyses can provide compelling and insightful results.

Cohen (2014) MIT Press
Creating Epochs: continuous data are cut into segments surrounding particular experiment events.

Edge artifacts result from applying temporal filters to sharp edges such as a step function, and produce a high-amplitude broadband power artifact that can last hundreds of milliseconds. These artifacts will always be present when there are non-continuous breaks, which happens at the first and last points of the EEG epochs.

If you are **re-analyzing a dataset** that has already been epoched and cannot be re-epoched from the continuous data, and if you are concerned that the epochs are too short and the time-frequency results might be contaminated by edge artifacts, you can use a “reflection” approach.
1) **Matching Trial Count across Conditions**: it is ideal for all conditions to have the same number of trials. Low trial count decreases signal-to-noise ratio and therefore makes the ERP more sensitive to outliers or nonrepresentative data.

2) **Filtering**: can help remove high-frequency artifacts and low-frequency drifts, and notch filters at 50 Hz or 60 Hz help attenuate electrical line noise.

3) **Trial Rejection**: removing trials that contain artifacts prior to analyses is important. Spatial Filtering: to help localize a result.

4) **Referencing**: Any activity present in the reference electrode will be reflected as activity in all other electrodes. Thus, choose your reference electrode(s) carefully and make sure the reference electrodes are properly placed and have a good, clean signal during subject preparation. Noise in the reference electrodes will turn into noise in the scalp electrodes.

(Re-)referencing

Cohen (2014) MIT Press
EEG Artifacts: Their Detection, Influence, and Removal

Most common artifacts: blinks, muscle movements, brief amplifier saturations, and line noise.

Removing Data Based on Independent Components Analysis (topography, time course, power spectrum)
Most common artifacts: blinks, muscle movements, brief amplifier saturations, and line noise.

-Removing Trials because of Blinks
-Removing Trials because of Oculomotor Activity

A better approach:
-Train Subjects to Minimize Artifacts
-Use a Paradigm that Minimizes Artifacts during Data Collection
Overview of Time-Domain EEG Analyses

Event-Related Potentials

Butterfly Plots

Filtering ERPs

Global Field Power/Topographical Variance Plots

Cohen (2014) MIT Press
Topographical Maps

Excellent and nearly ubiquitously used method for showing the spatial distribution of EEG results.

Interpolated maps are easier to interpret.

Plotting topographical maps over time facilitates rapid data quality inspection.

Cohen (2014) MIT Press
“In EEG as well as ERP map series, for brief, subsecond time periods, map landscapes typically remain quasi-stable, then change very quickly into different landscapes” (Lehmann 1971).

(A) Potential map series from an ERP in response to a reversing checkerboard and shown at 4 ms intervals.

(B) Result of the spatial cluster analysis applied to the map series shown in A. A cross-validation procedure identified six maps as optimally explaining the whole data set.

(C) Plot of the Global Dissimilarity (GD) for the ERP shown in A, which is a general measure of topographic similarity between two maps, here between maps of successive time points. High values indicate time points where the topography changes drastically. Colored areas under this curve denote the periods over which the above defined cluster maps best explained the data. Note that each of these maps is present for a certain time period (a functional microstate).
An ERP image is a 2-D representation of the EEG data from a single electrode. Rather than all trials averaged together to form an ERP, the single-trial EEG traces are stacked vertically and then color coded to show changes in amplitude as changes in color.

1) Carefully **watch the EEG throughout the entire recording session** so that you can detect problems with the recordings (e.g., loose electrodes, blinks, eye movements, muscle noise).

2) Use a **reasonably high sampling rate, keep filters open.**

3) **Keep subjects happy:**
   
   i. First, talk to the subject. If a subject isn’t doing well (e.g., in terms of behavioral accuracy or artifacts), don’t be shy about telling them that, because poor performance and artifact-laden data won’t be of much use to you.
   
   ii. Second, make sure that the blocks of trials are a reasonable length. If the blocks are too long, the subject’s attention is likely to wane toward the end.
   
   iii. Third, due to the long duration of a typical ERP experiment, it is helpful to provide snacks and drinks, usually 30-50% of the way through the session.
   
   iv. Play background music in the chamber while the subject is doing the task. In fact, we suggest to the subjects that they bring CDs of their favorite music with them. Of course, the music produces some distraction from the task, and the sounds will generate ERP activity. However, I believe that the music is less distracting than the alternative, which is mind-numbing boredom. And any ERP activity generated by the music will be unrelated to the stimuli and will just add a small amount of noise to the EEG.

Luck (2014) MIT Press
Thank you!
Reading List