Introduction to EEG Decoding for Music Information Retrieval Research

DATA ACQUISITION AND PREPROCESSING

Electroencephalography (EEG)

- EEG is the measure of electrical activity of the brain
- Sufficiently many neurons (hundreds to tens of thousands) firing synchronously will produce an electrical field strong enough to be measured noninvasively at the scalp
- EEG is used here to refer to noninvasive measures – compare to electrocorticography (ECoG), in which electrodes are placed directly onto the cortical surface

General Acquisition Steps

- Amplification
  - EEG SNR thought to be around -20 dB
  - signals in microvolt (μV) range
- Filtering
  - can be done at acquisition or offline
- Digitizing (sampling)
  - data are sampled at acquisition
- Storage
  - convention is one time series per channel
  - stored in electrodes-by-time matrix

EEG Equipment Overview

- electrodes
  - dry vs. wet (soak in solution / apply gel)
  - active vs. passive
  - net / cap / sticky (individual) / headset
- amplifier
  - usually battery-powered (DC)
  - from analog to digital signals
- recorder
  - connection: optical / wireless

EEG Electrodes

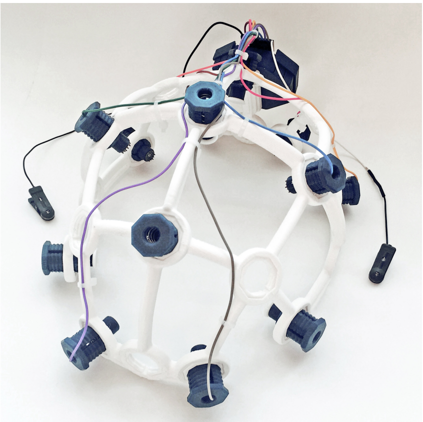
electrode net (EGI)

electrode cap
(Biosemi)

individual (sticky)
electrodes

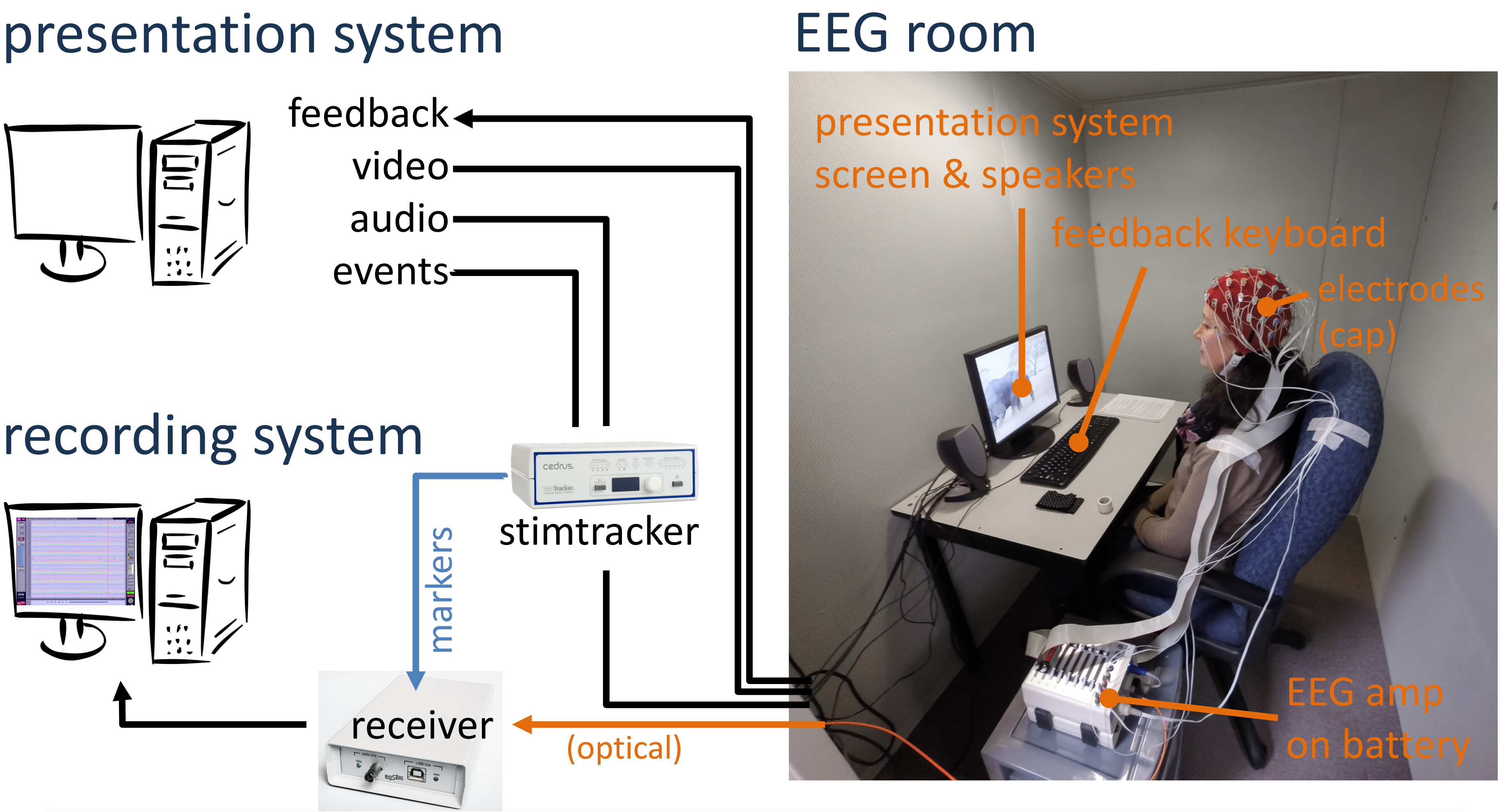
headsets

http://emotiv.com



http://openbci.com

Typical Lab Recording Setup



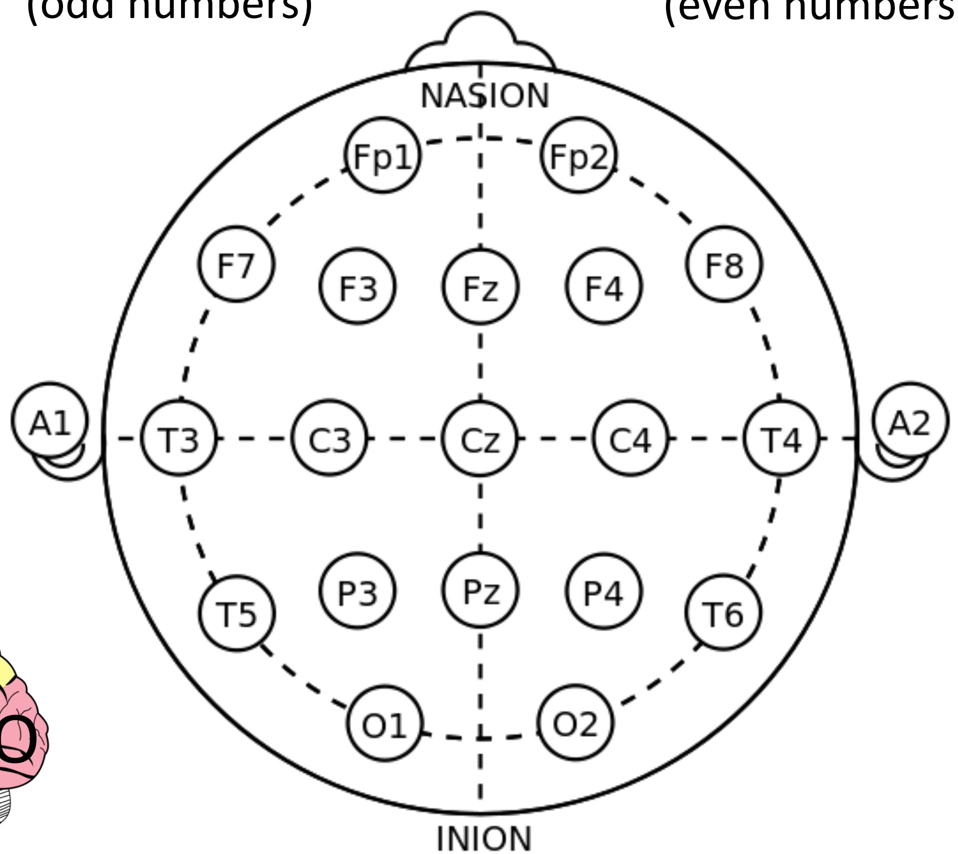
Electrode Naming Conventions

The International 10–20 System

left hemisphere
(odd numbers)

midline/zero
(z)

right hemisphere
(even numbers)



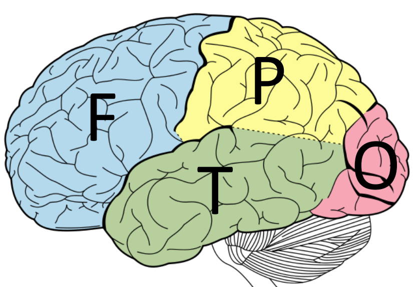
frontal polar (Fp)

frontal lobe (F)

earlobes (A)
central (C)
temporal lobe (T)

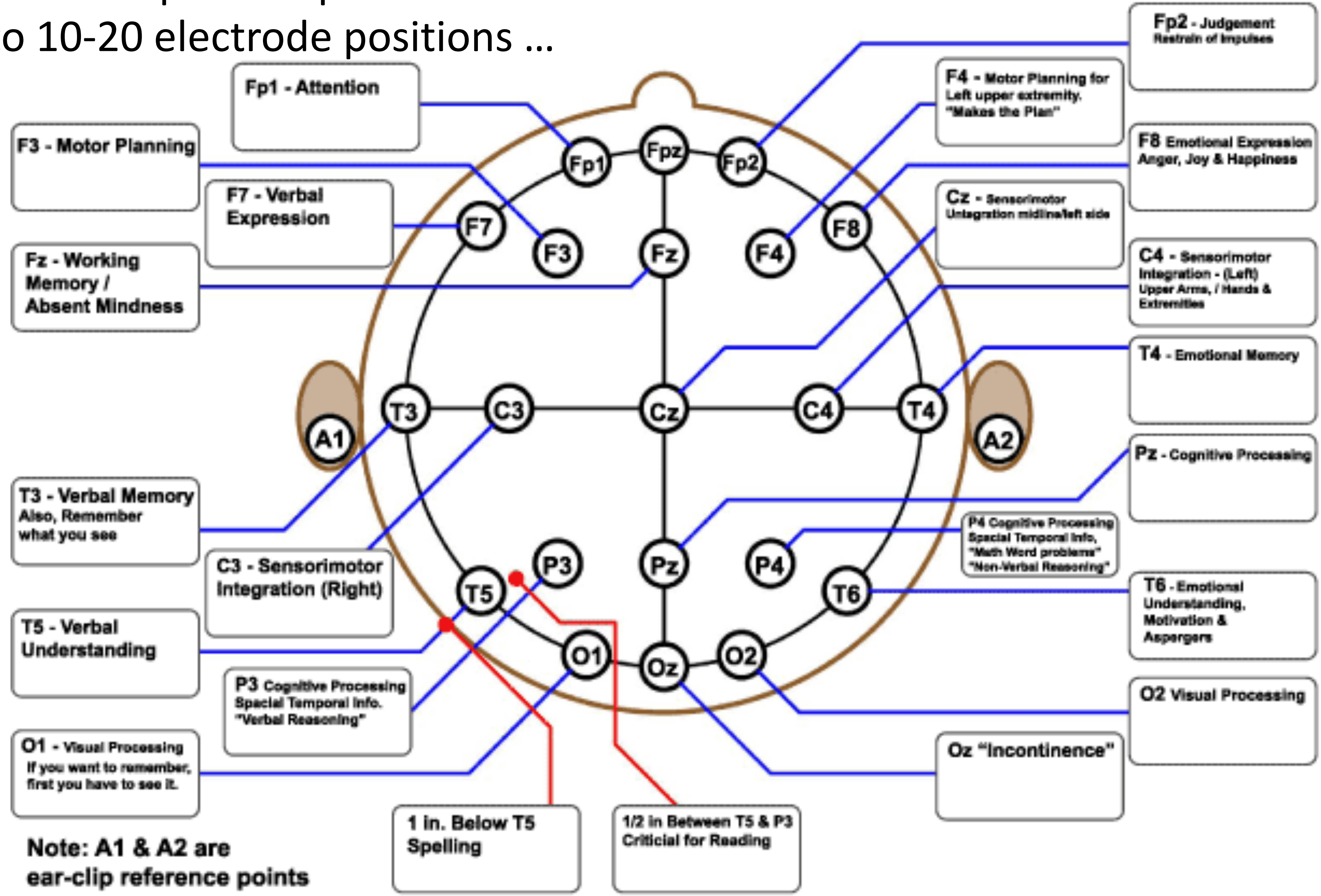
parietal lobe (P)

occipital lobe (O)



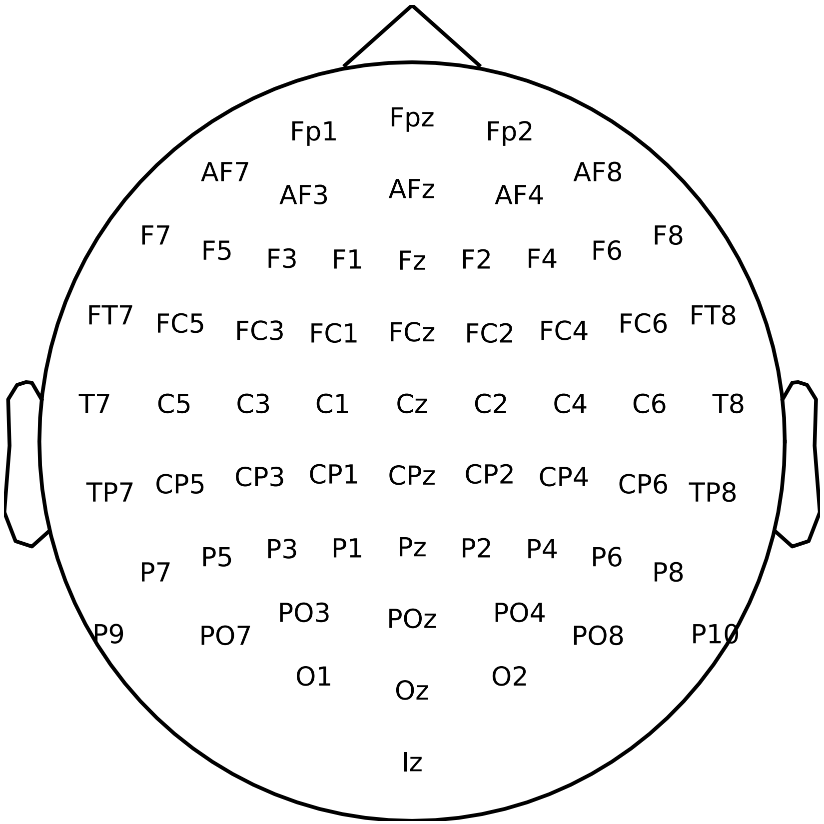
images: public domain

An attempt to map basic brain functions to 10-20 electrode positions …

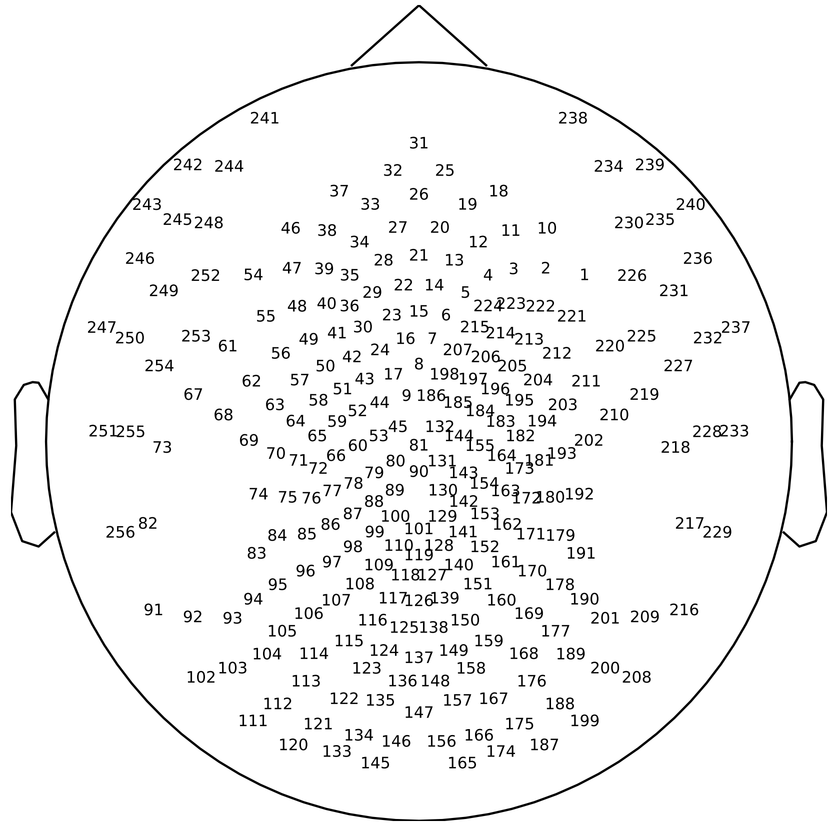


source: http://www.edmontonneurotherapy.com/Edmonton_Neurotherapy_QEEG_brain_mapping.html

Some Electrode Montages



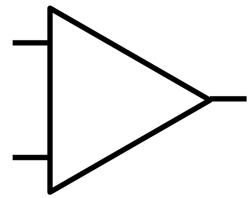
64 electrodes cap (Biosemi)



256 electrodes net (EGI)

Montage Types

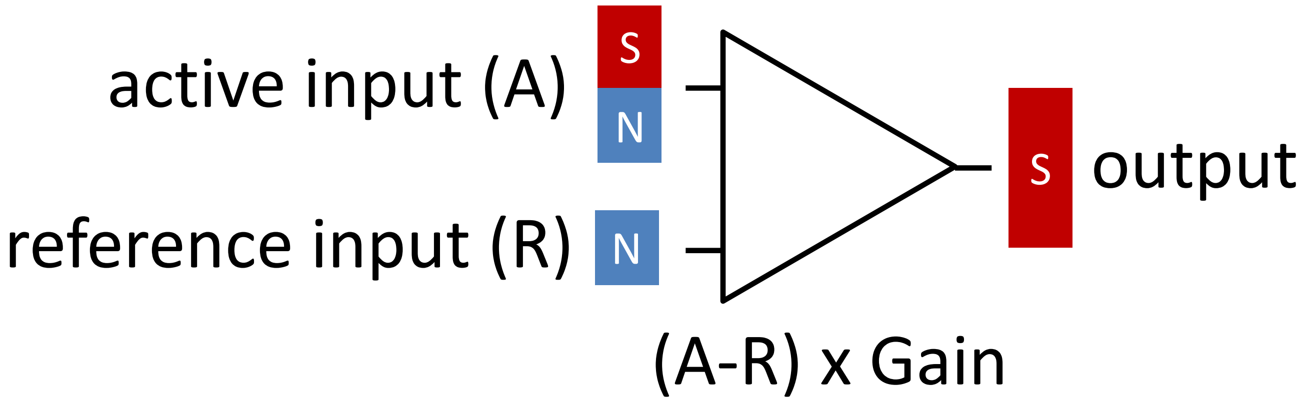
- electric potentials are only defined with respect to a **reference electrode** (“zero level”)



- monopolar
  - potential difference between reference electrode and electrode of interest
- bipolar
  - 2 electrodes per 1 channel
  - 1 individual reference electrode for each channel
- referential
  - 1 **common reference** electrode for all channels

Referencing

- goal: choose reference to capture the noise



Popular Common References

- one mastoid (e.g., TP10)
- linked mastoids
- vertex electrode (Cz)
- single or linked earlobes
- nose tip

- reference-free recording with **active electrode systems** (e.g., Biosemi Active Two)
  - reference chosen during data import

Re-Referencing

- change reference during data import
  = linear transformation

- **average reference** often applied for high-density EEG recordings
  - assumption: if sufficiently dense and evenly distributed, sum of electric field values recorded at all scalp electrodes is always 0 by Ohm's law
  - > any differences would be noise

Sampling

- similar to recording / analyzing audio

- part of analog-to-digital conversion
  – too low -> aliasing [Nyquist–Shannon Theorem]
    - low-pass filter at Nyquist-frequency
  – too high -> unnecessarily large data files
  – better over-sample than under-sample

- down-sampling as dimensionality reduction

Real-Time EEG Analysis

- typical application: Brain-Computer Interfaces
- not all systems allow real-time data access
  - usually through streaming (e.g., TCP/IP)
  - might require extra SDK license
- how many channels?
  - bandwidth limit (especially wireless)
  - processing load limit (especially mobile devices)
- special method requirements (e.g., buffering)

Spatial filters for EEG

- EEG data are noisy and also record redundant information from adjacent electrodes.
- One way to improve SNR and concentrate relevant information into a lower-dimensional subspace is to compute a **spatial filter** over the data.
- Spatial filters typically comprise a linear weighting of the electrodes (a vector of length nChannels).
- Multiple filters may be computed at once and represented in an "un-mixing" matrix.

Spatial filters for EEG

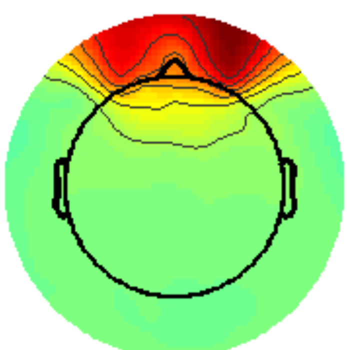
- Spatial filters are typically computed subject to the optimization of some criterion.
- Example spatial filters
  - Principal Components Analysis (PCA): Maximize variance explained
  - Independent Components Analysis (ICA): Derive temporally independent activations[1,2]
- Techniques developed specifically for EEG
  - Reliable Components Analysis (RCA): Maximize covariance of two data frames[3]
  - Common Spatial Pattern (CSP): Minimize variance for one stimulus condition, maximize for other[4]

[1] Bell et al. (1995). Neural Computation.[2] Jung et al. (1998). Adv Neur Inf Proc Sys. [3] Dmochowski et al. (2012). Frontiers in Human Neuroscience. [4] Blankertz et al. (2008). IEEE Signal Processing Magazine.

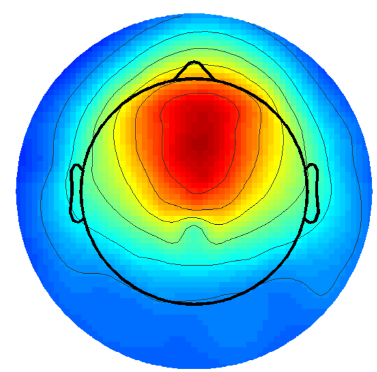
Spatial filters for EEG

- It's often helpful to visualize the spatial filter on a topoplot of the scalp.
- Important! Do not plot the weight vector directly. Instead, plot the **forward-model projection** of the weight vector.[1,2]
  - Consider spatial filter matrix W, data covariance matrix R
  - Forward model $A = RW(W^TRW)^{-1}$

Example Independent Component related to eye movements

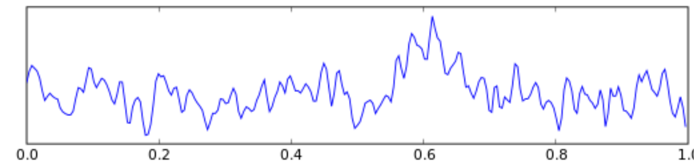


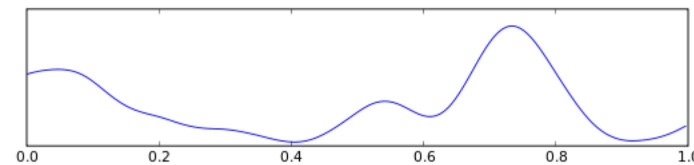
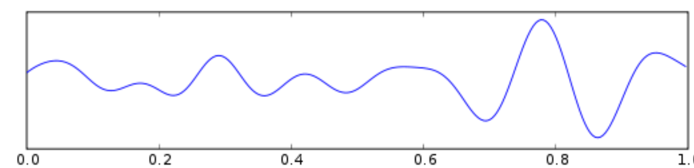
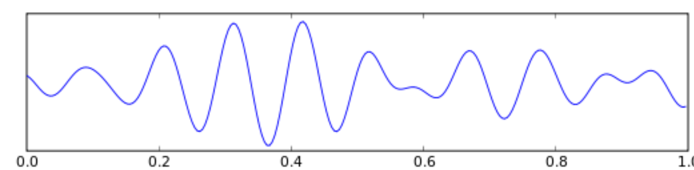
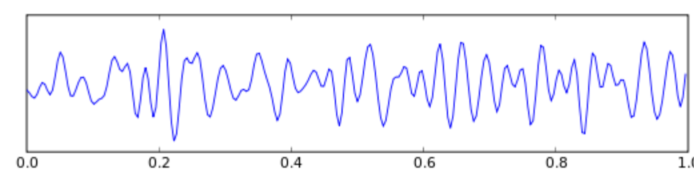
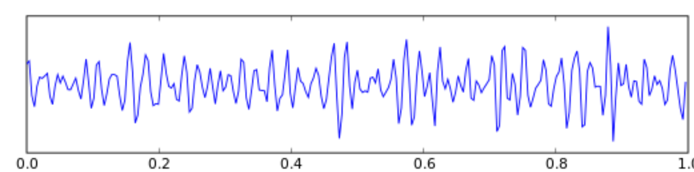
Example Reliable Component related to naturalistic music listening



[1] Haufe et al. (2014). NeuroImage. [2] Dmochowski et al. (2012). Frontiers in Human Neuroscience.

EEG Oscillations



delta	< 4 Hz	
theta	4 – 8 Hz	
alpha	8 – 15 Hz	
beta	15 – 30 Hz	
gamma	30 – 100 Hz	

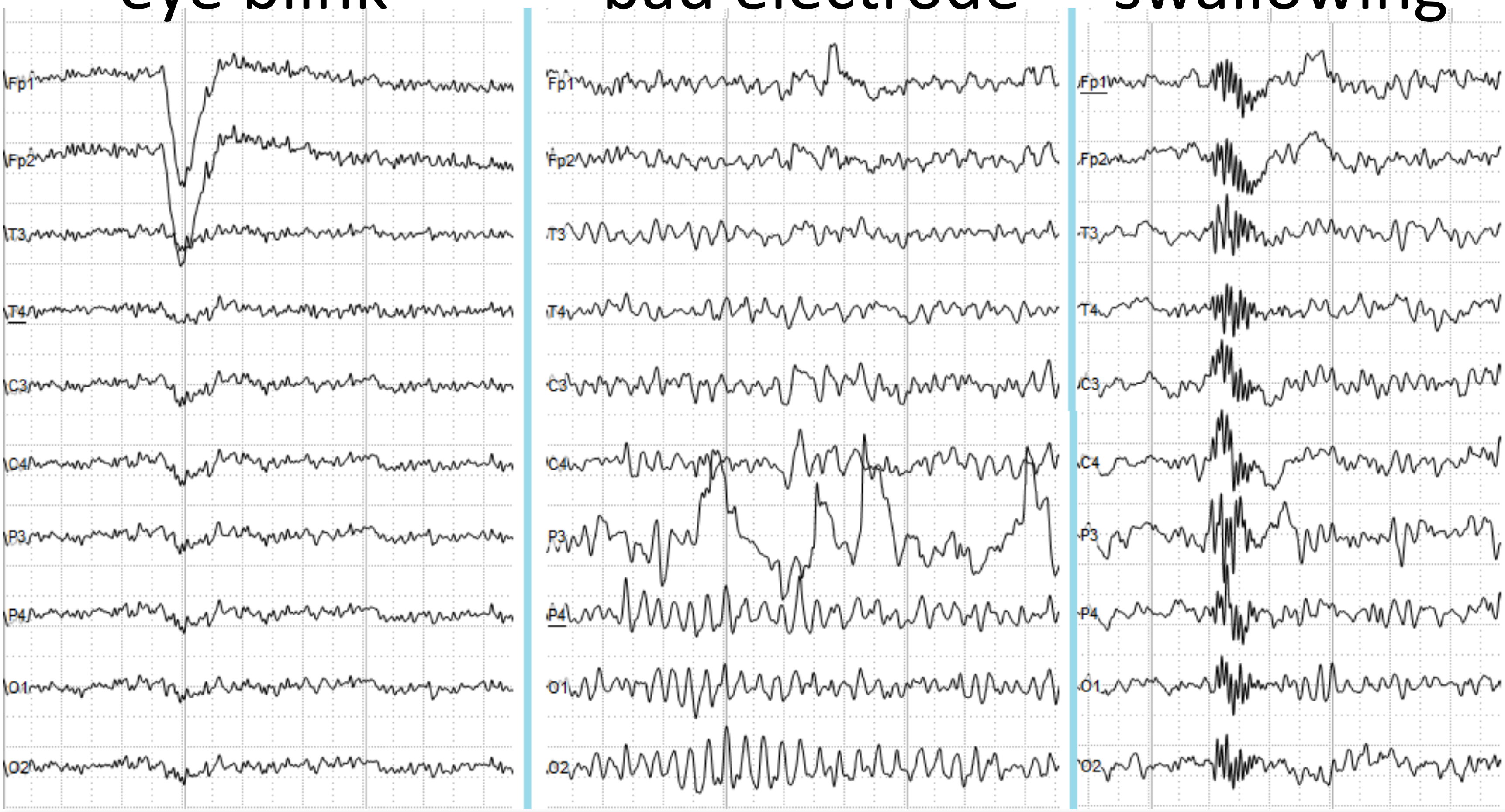
EEG Artifacts

a) physiologic – from the subject
   (sources other than the brain)
   – muscles (eyes, jaws, heart, …)
   – sweat (impedances change!)

b) extra-physiologic – from outside the body
   – 50/60 Hz AC noise
   – bridged electrodes (electrolyte/salt bridges)
   – bad/dead electrodes (high impedance)

Common Artifacts

eye blink bad electrode swallowing



Dealing with EEG artifacts

- **Exclude** the data – possible when working with a large number of trials and/or electrodes
- **Remove** the artifact by filtering (e.g., high-frequency muscle artifacts), regression (e.g., eyeblinks), identifying and removing artifact components (e.g., eyeblinks)
- **Impute** affected data – e.g., replace a bad electrode with the spatial average of its neighbors

Removing eye artifacts with Extended ICA

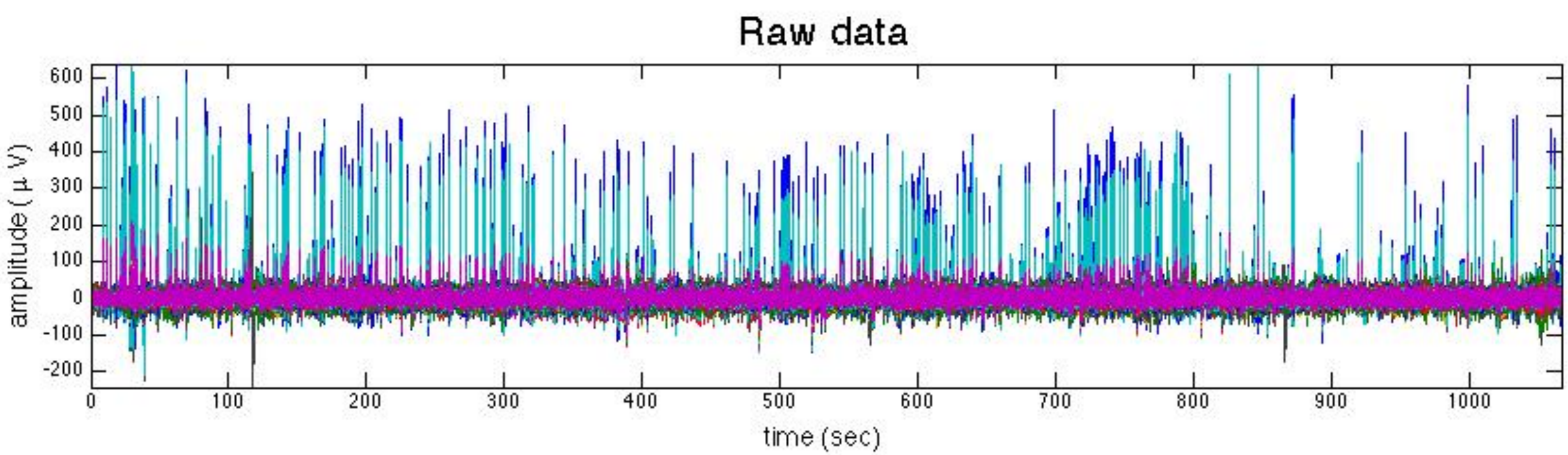
ICA is a validated method for removing eye artifacts from EEG data, and is available in the widely used toolboxes[1,2]

- Convert data from **electrode** space to **component** space.
- Eye activity should concentrate into a few components.
- Set those component activations to zero and convert back to "clean" electrode space.

[1] Bell et al. (1995). Neural Computation. [2] Jung et al. (1998). Adv Neur Inf Proc Sys.

Preprocessing example: ICA

- 18 minutes of music listening (4 4.5-min trials)[1]
- EEG recorded with 128 electrodes, 124 used for analysis; data bandpass filtered (0.3-50 Hz) and downsampled to fs=125.
- No bad electrodes; “good” participant (sits still)
- Raw data: We have overplotted all 124 electrodes to get sense of activity over time.



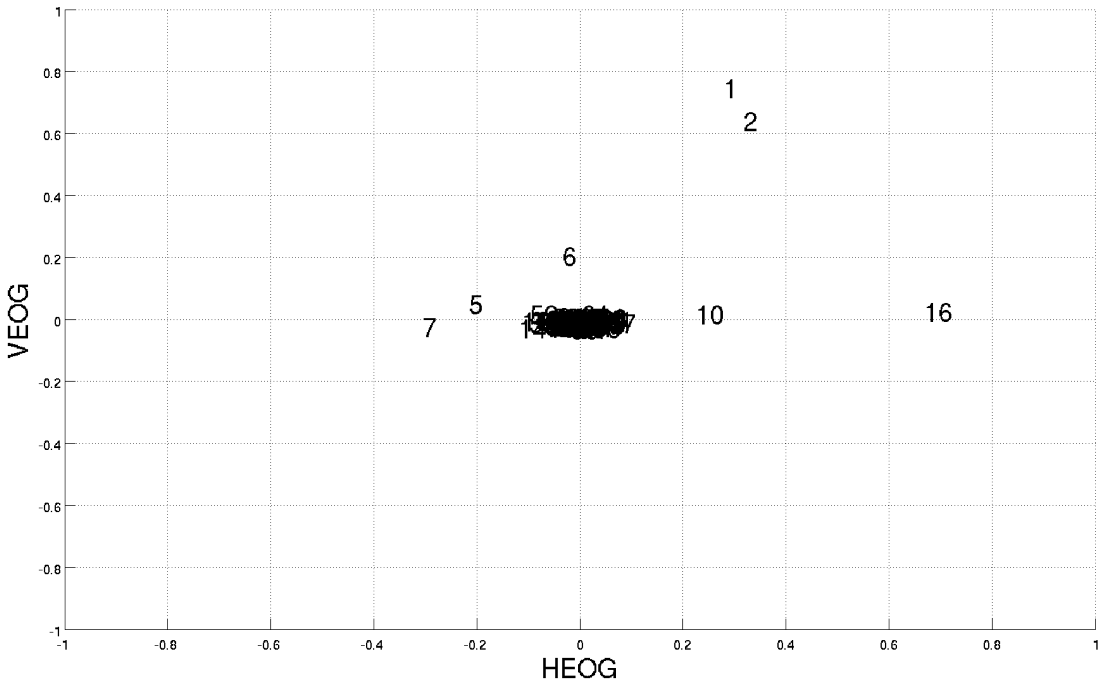
[1] Kaneshiro (2016). Doctoral Dissertation.

Preprocessing example: ICA

- We have already computed HEOG and VEOG channels using combinations of electrodes to the sides and above/below the eyes, respectively.
- We then compute ICA and use the **spatial filter** W to convert the data from electrode space to component space.
- We correlate the timecourse of each ICA component with each of the EOG channels to identify correlated components.
- We also visualize the **forward-model projection** of the components (weight vectors) on a topographical map.
- We will use the correlations, along with visual inspection of the activation and topography, to identify EOG components.
  - Automatically reject any component for which $|\rho| \geq 0.3$
  - By inspection, reject components for which $0.2 \leq |\rho| < 0.3$

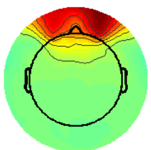
Preprocessing example: ICA

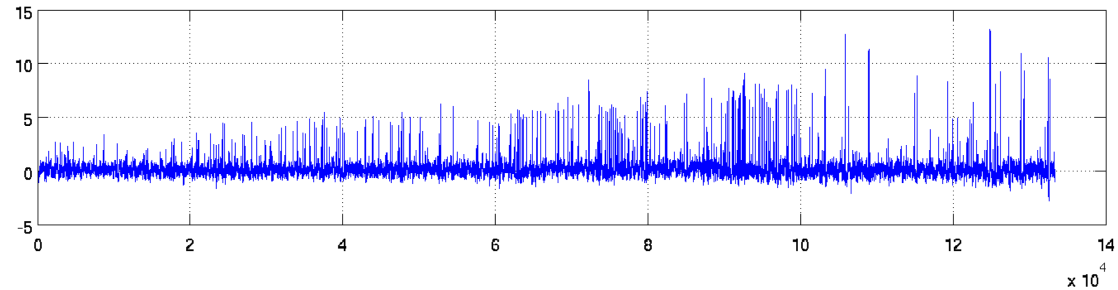
Components 1, 2, 16 are over 0.3 threshold – automatic reject.
Components 6, 7, 10 are marginal – will check component characteristics.
Component 5 is outside of cloud but not high enough to trigger manual reject.



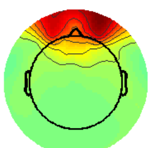
Preprocessing example: ICA

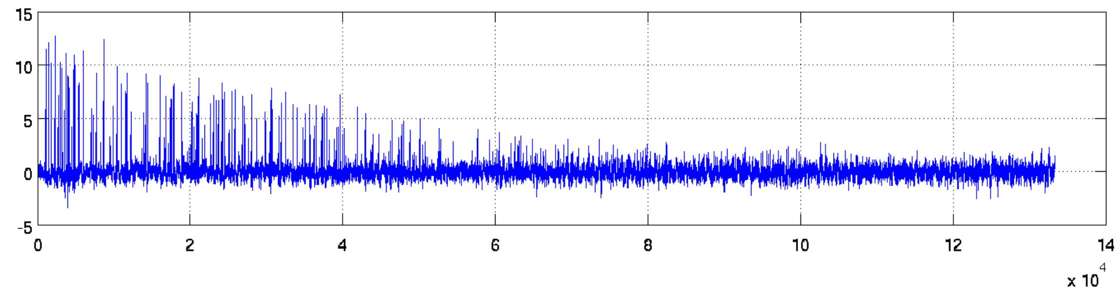
Source 1
corrV = 0.7562
corrH = 0.2935



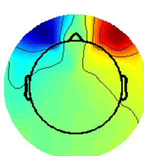


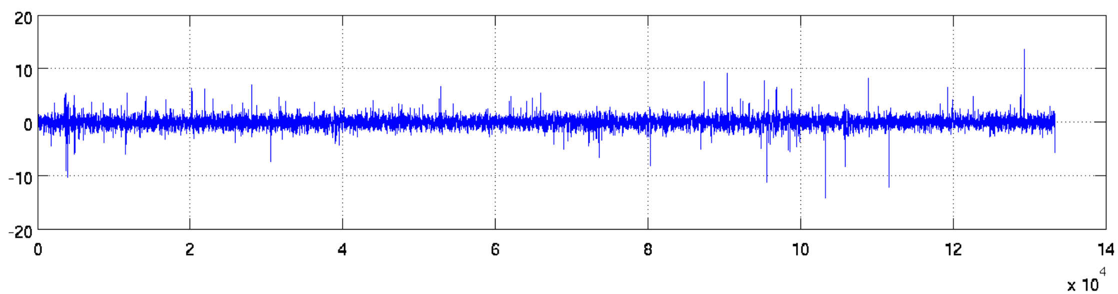
Source 2
corrV = 0.6502
corrH = 0.3332





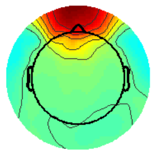
Source 16
corrV = 0.0343
corrH = 0.6975

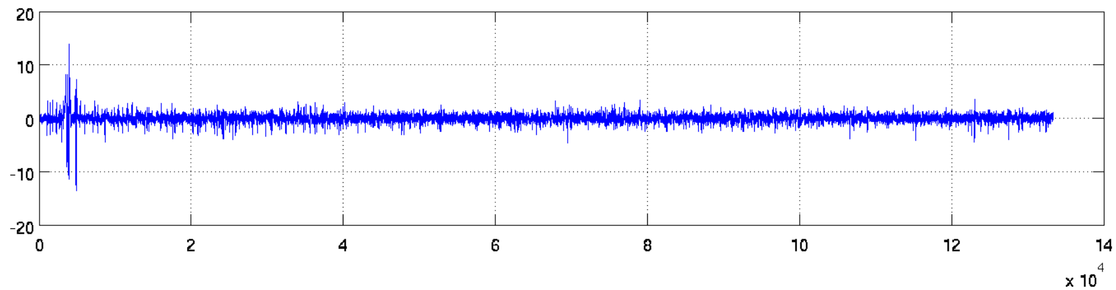




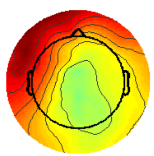
Preprocessing example: ICA

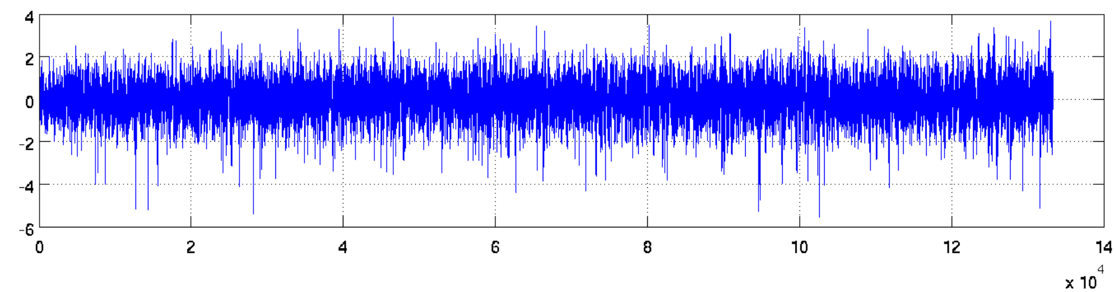
Source 6
corrV = 0.2131
corrH = -0.0174



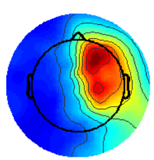


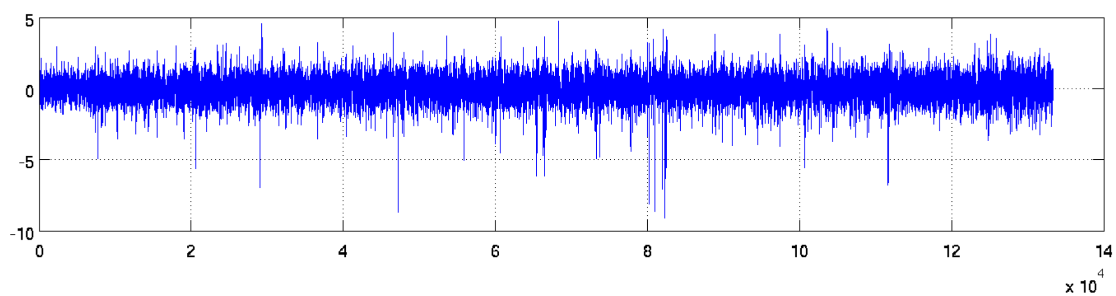
Source 7
corrV = -0.0157
corrH = -0.2899





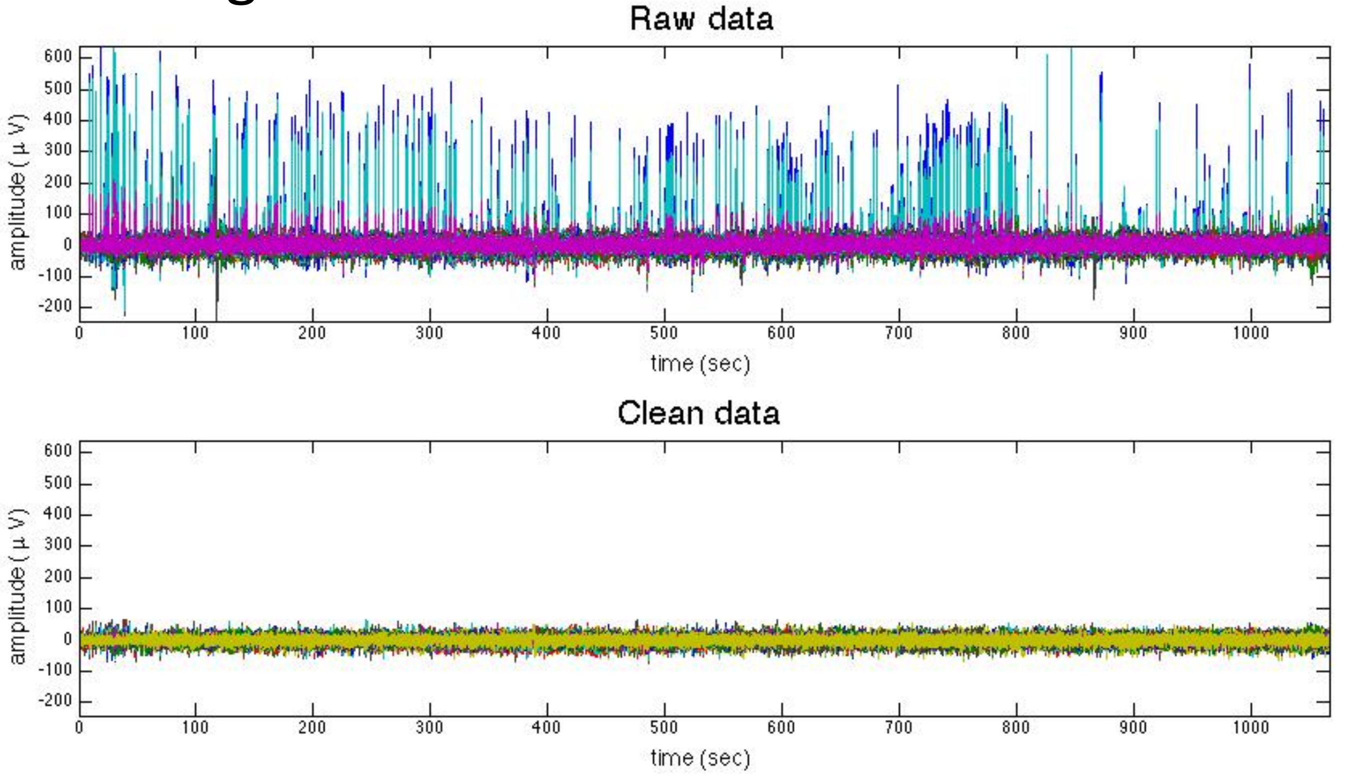
Source 10
corrV = 0.0250
corrH = 0.2538





Preprocessing example: ICA

- We set activations for high-reject components to zero.
- Convert back to "clean" channel space, remove noisy transients, convert to average reference.



Event-Related Potentials (ERPs)

Definition:

"Scalp-recorded neural activity that is generated in a given neuroanatomical module when a specific computational operation is performed."[1]

Not the focus of today's tutorial, but makes up the majority of the research literature on music and EEG.

[1] Luck (2005). *An Introduction to the Event-Related Potential Technique.*

Event-Related Potentials (ERPs)

Idea:

- averaging over many trials (epochs) averages out random brain activity and keeps only the relevant waveform
- compare waveform components

Event-Related Potentials (ERPs)

Interpretation:

observe:

- time course …
- amplitude …
- distribution across scalp …

differences in ERP

infer:

- timing …
- degree of engagement …
- functional equivalence …

of underlying cognitive process

Event-Related Potentials (ERPs)

- example:
  musical stimuli (dotted) vs. spoken syllables (solid)

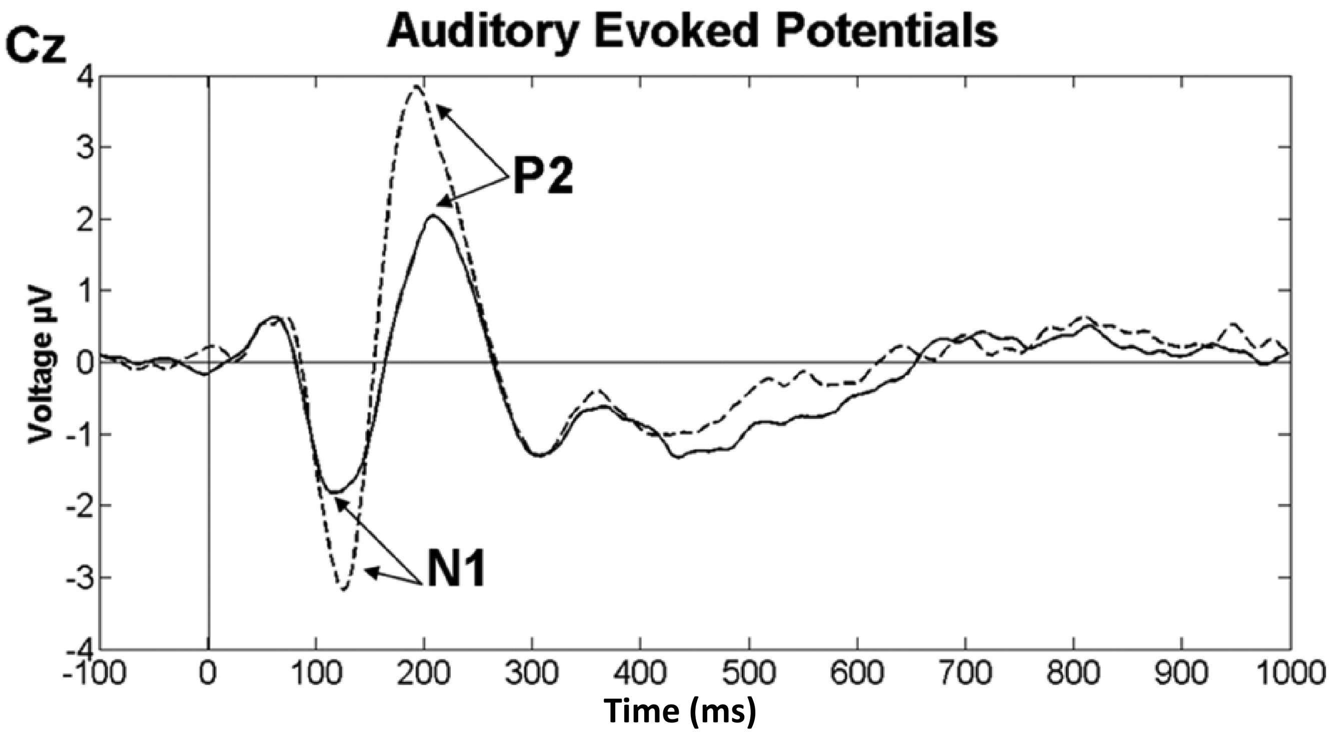


figure from Meyer et al., "Short-term plasticity in the auditory system: differential neural responses to perception and imagery of speech and music" in Restorative neurology and neuroscience 25(3-4):411-31, February 2007.

Experiment Design: General

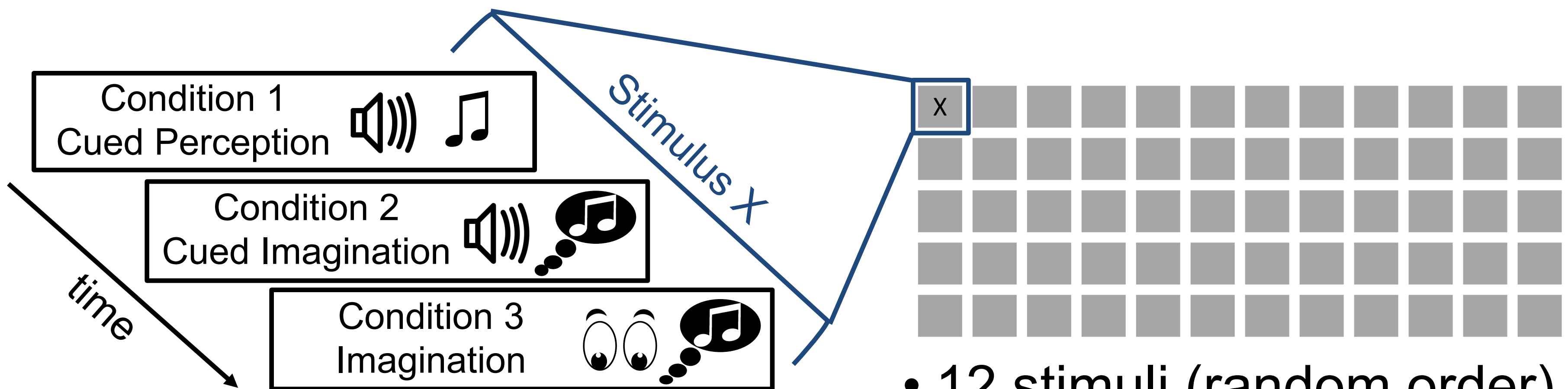
- general design / analysis approach
  - epoched (ERP analysis), i.e., average over **many** short time windows (epochs) to reduce noise
  - single-trial
- active vs. passive task
- focus on a specific effect, exclude secondary effects
- how many trials?

Experiment Design: Timing

- separate events in time (avoid overlaps!)
- self-paced vs. controlled timing
- constant or variable inter-trial timing
  - anticipation vs. surprise effect
- event marker / trigger recording
  - for time-locking events / stimuli
  - confirm values and timing accuracy!!!

Experiment Design: Blocks

- vary conditions/stimuli within blocks rather than between blocks



- 12 stimuli (random order)
- repeat for 5 blocks

Experiment Design: Artifacts

- avoid / reduce distractions (phone!)
- avoid / reduce movement (good chair!)
- avoid fatigue, allow pauses

- electrically (and acoustically) shielded room
  - remove unused equipment
- test different electric circuits
- control light & temperature in recording room

Experiment Design: Technical

- amplifier and filter settings
- sampling frequency
  - use more than just 2x target frequency range (!)
- number, type, location of electrodes
  - impact on preparation time & data volume
- reference electrode(s)

Experiment Design: Technical

- electrode localization equipment?
  – better spatial precision than general montage data
- feedback & trigger device(s)?
  – intuitive use
  – timing
- additional physiological measures?
  – eye-tracking , EOG (eye muscles), ECG (heart) etc.
  – helps cleaning the data

Experiment Design

- Be aware of biases!
  - participant selection
  - participant group assignment
  - selection of stimuli

- most importantly:

Test, test again and pilot!!!
(Be prepared for things to go wrong!)

Live Demo – Part 1

- importing / pre-processing of a single (1h) EEG recording session
  - from OpenMIIR: https://github.com/sstober/openmiir
  - using MNE-Python: https://github.com/mne-tools/mne-python

- jupyter notebook available at: https://github.com/sstober/ismir2016eeg-tutorial