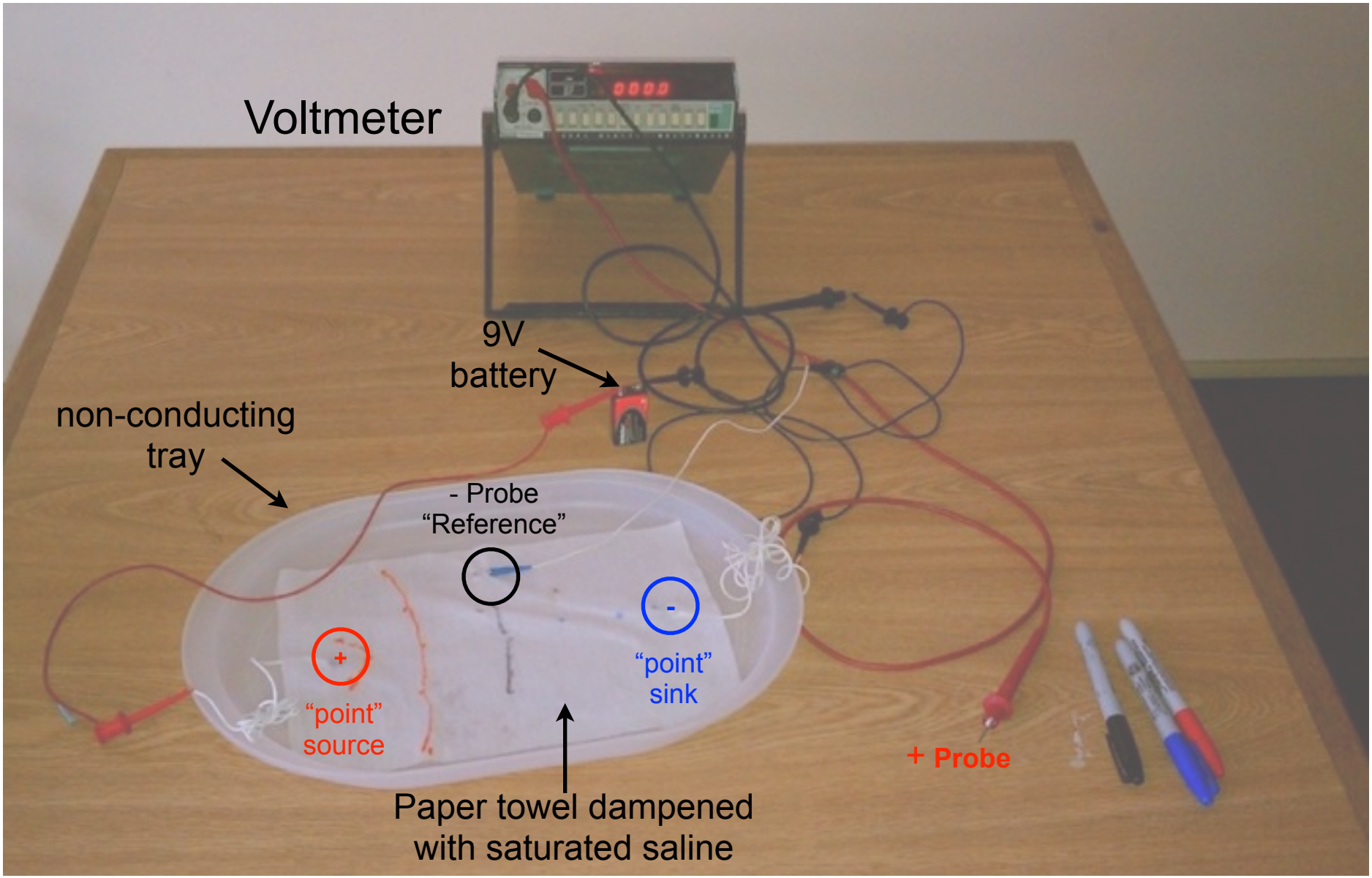
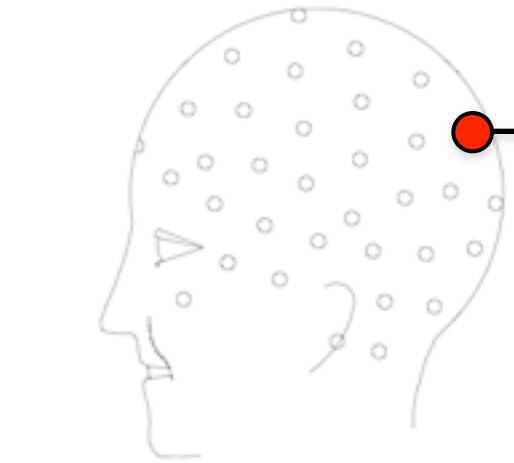
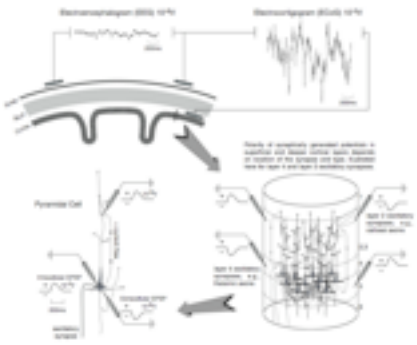
# DIY volume conductor



# EEG: Recording the neural symphony

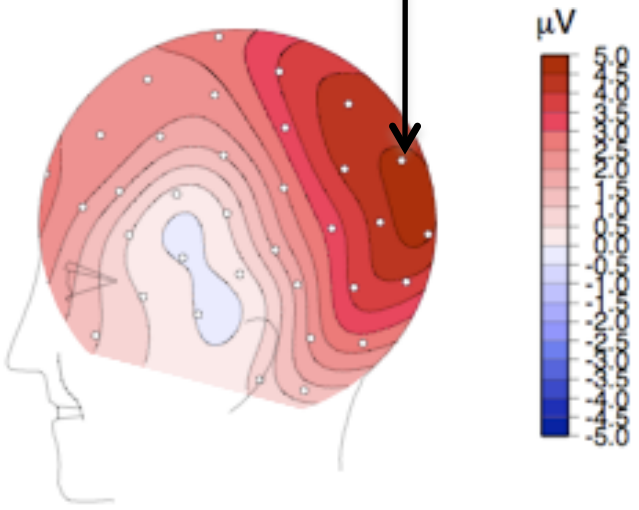
- Brain-generated electrical potentials (Volts) measured over time at the surface of the scalp





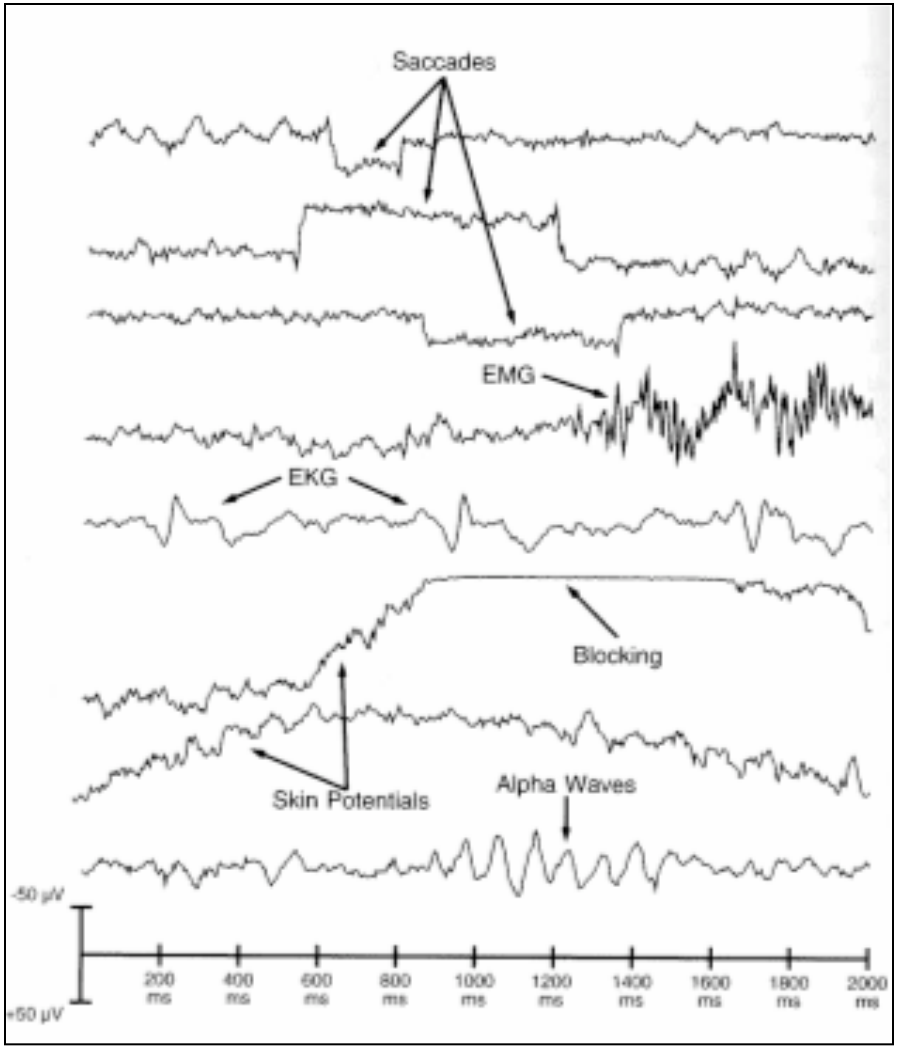
voltage x time (space constant)

voltage x space (time constant)




*t* = 600 milliseconds

# … on the runway at Lindberg Field



# EEG recordings: sum of many electrical sources - some in brain, many not

- Large artifacts: 50 - 500 μV
  - Biopotentials: eyeballs, muscle activity, skin
  - Non-biological electrical interference, e.g., 60Hz
- Small “background” EEG: 10 - 100 μV
- Tiny **E R P** s: 0.1 - 10μV

# Event-related brain potentials: ERPs

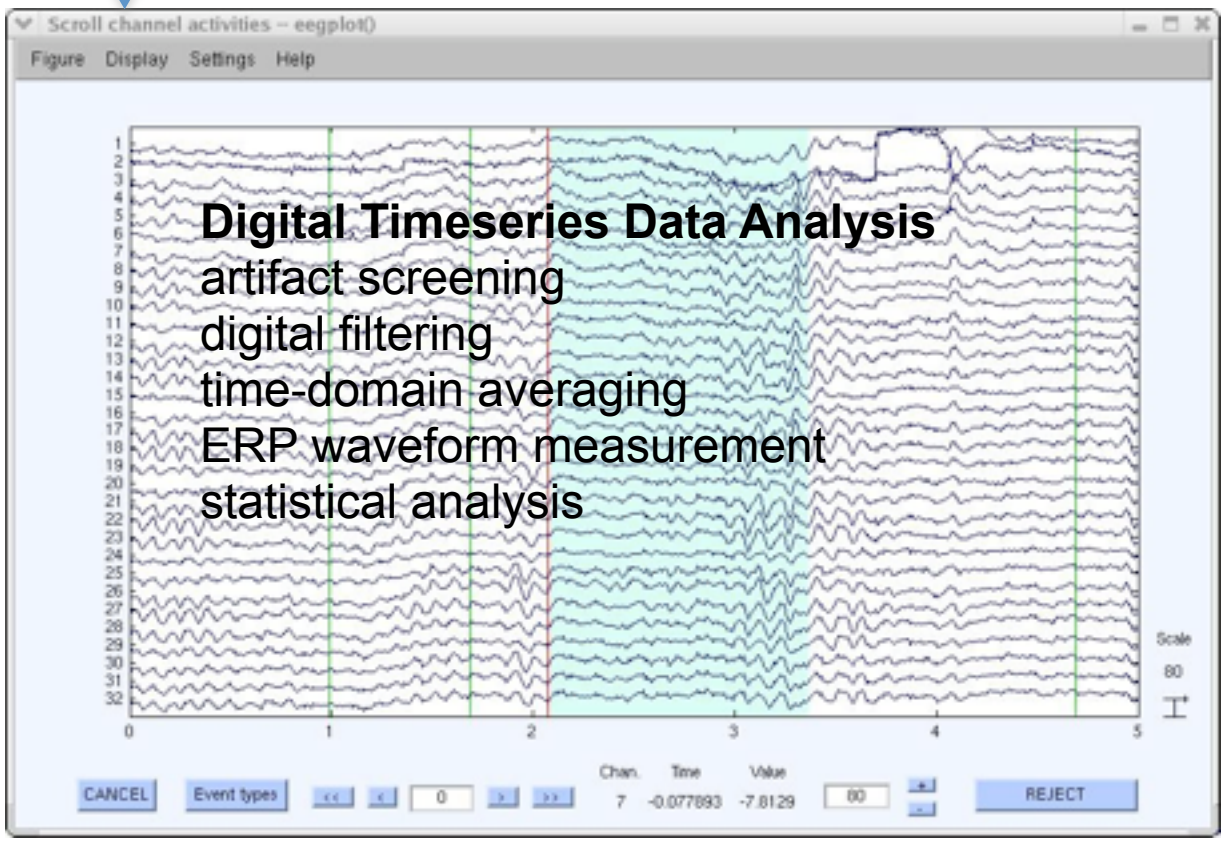
- So ... how do we find the tiny ERP in all this junk?
- Nifty engineering
- Careful experimentation

**Digitization**
sampling rate
bits per sample

**Differential amplification**
gain
high pass filter
low pass filter

Analog to Digital Converter

Multichannel EEG




**Digital Timeseries Data Analysis**
artifact screening
digital filtering
time-domain averaging
ERP waveform measurement
statistical analysis

**Electrodes**
material
montage
reference

# EEG lab equipment

Data acquisition

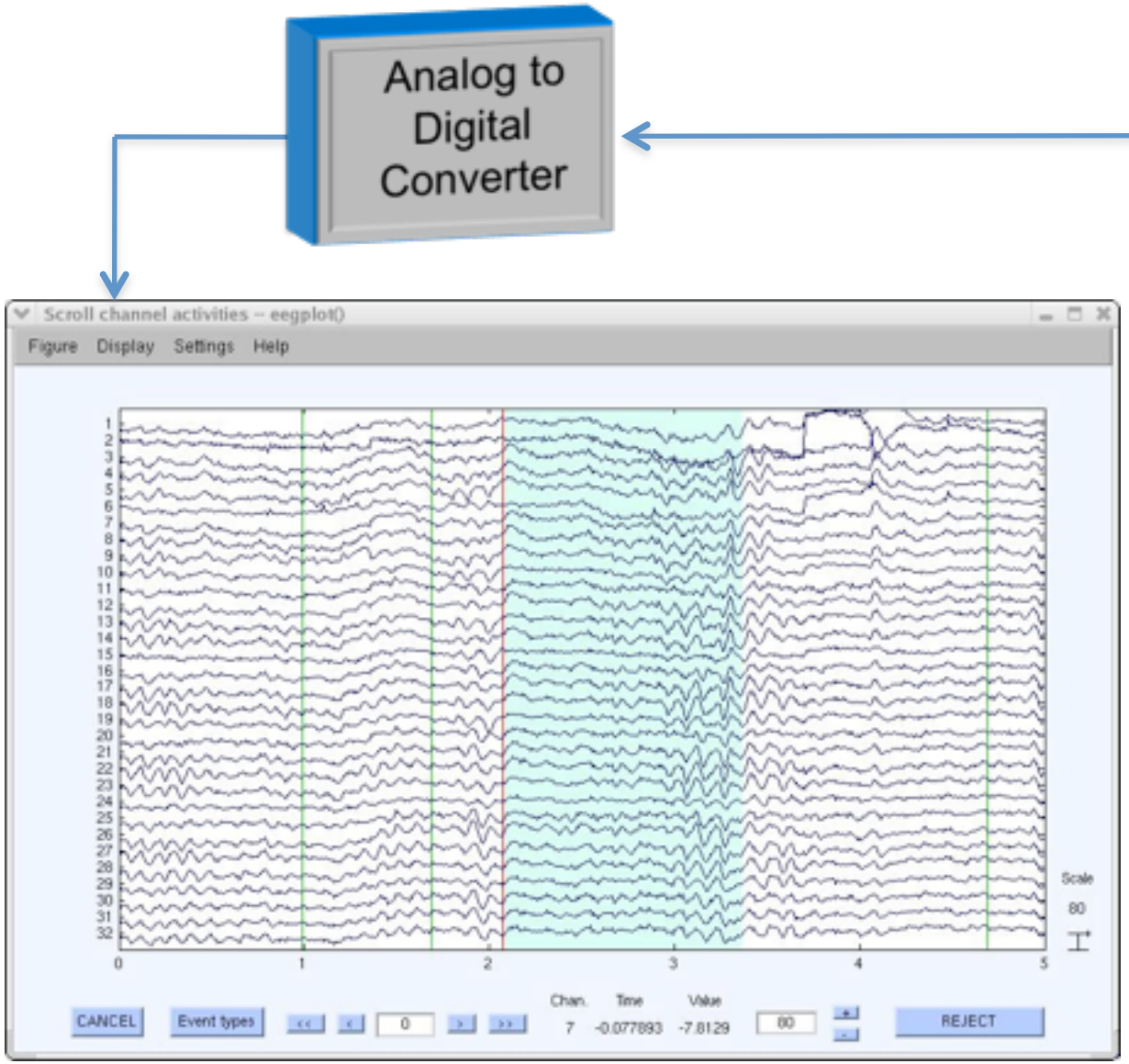
Stimulus presentation

32 channel EEG

Shielded testing chamber

Experimenter working area

Participant area

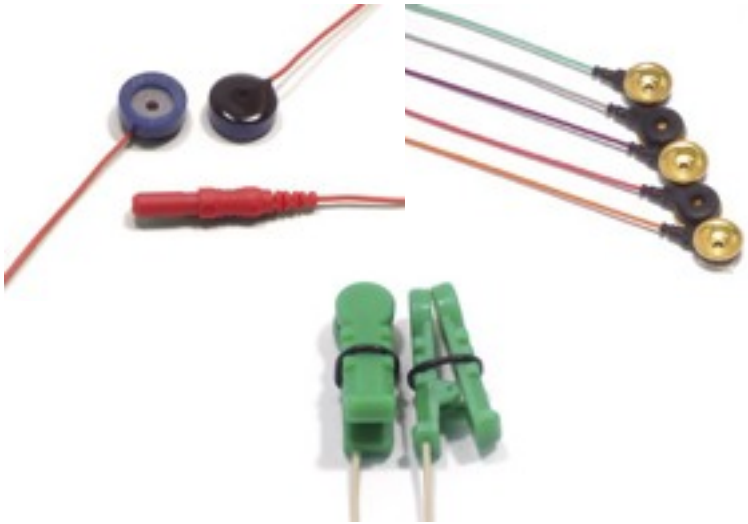



**Electrodes**
material
montage
reference

**Electrode** = conductive material attached to a wire; usually a metal disk that forms an electrical connection with the scalp via a conductive gel.

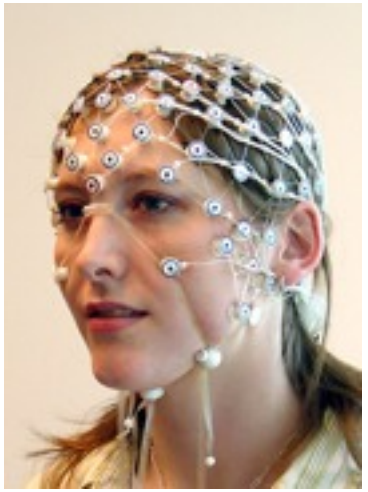
Good choice for most purposes: **tin**

Current fashion: ***scintered Ag/AgCl*** (silver-silver chloride) an improvement over plated **Ag/AgCl** electrodes – silver electrodes with thin coating of silver chloride that must be maintained.

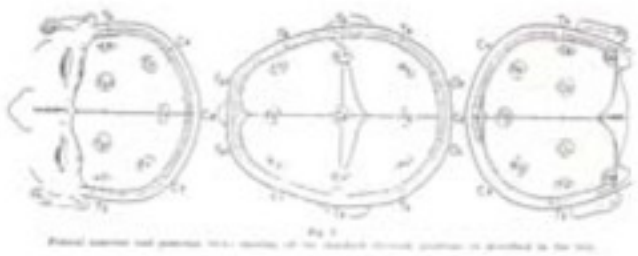


**Don't mix electrode metals!!**

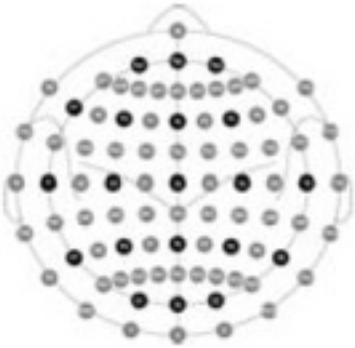
Typically retained in plastic mounts attached to elastic caps or nets



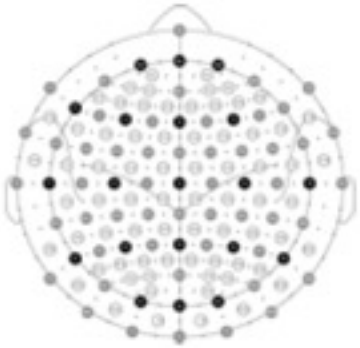
# Electrode locations ... where, given different sized heads?



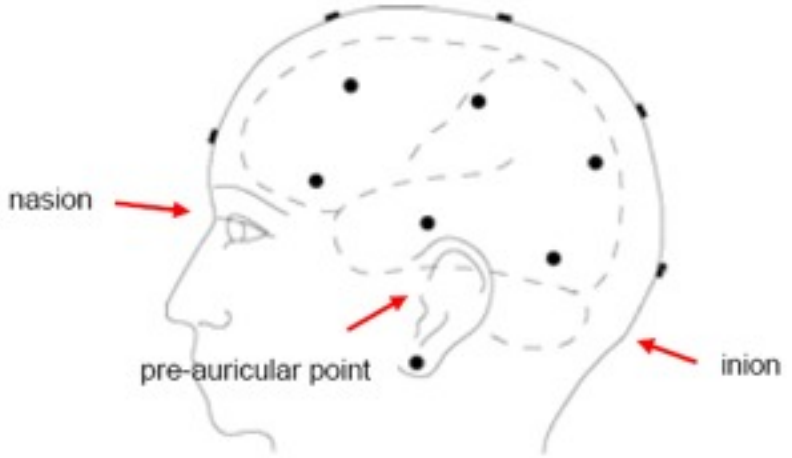
10-20 system



10-10 system



10-5 system

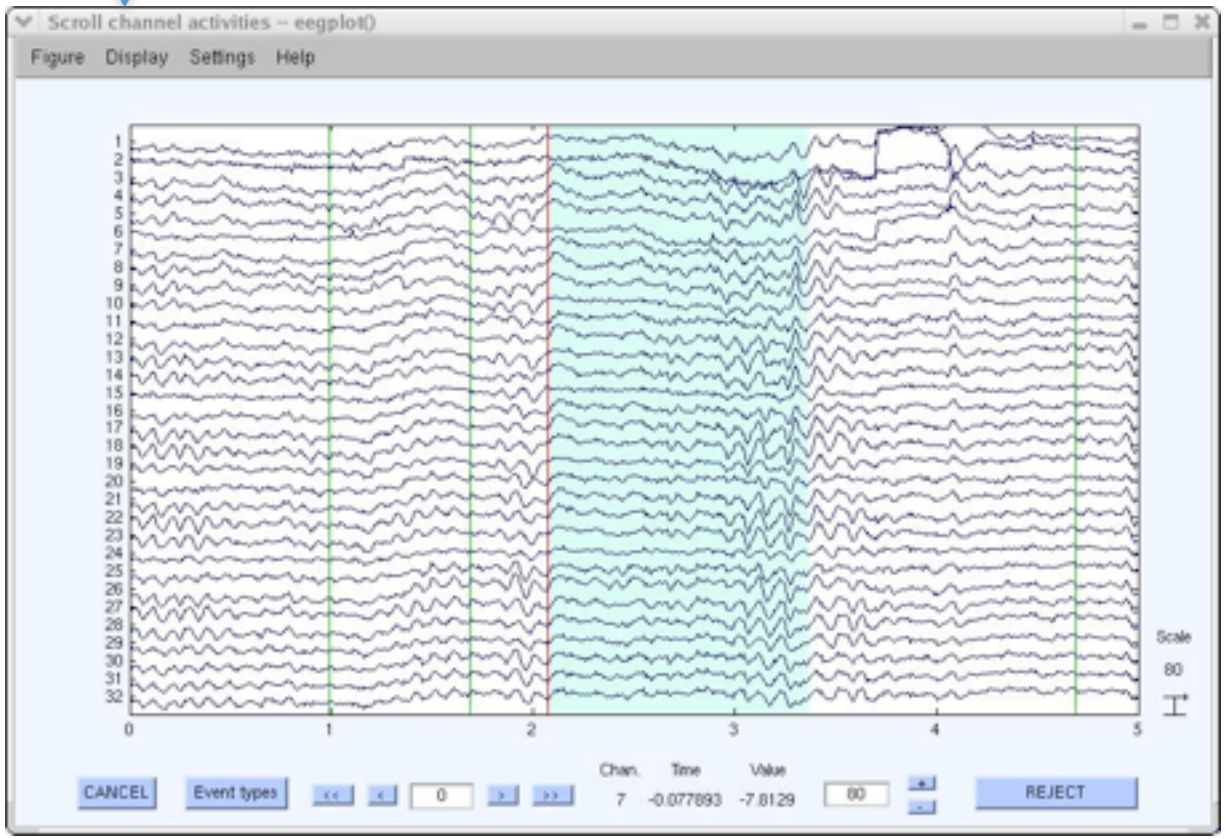



[Jasper, 1958]

**Differential amplification**
gain
high pass filter
low pass filter

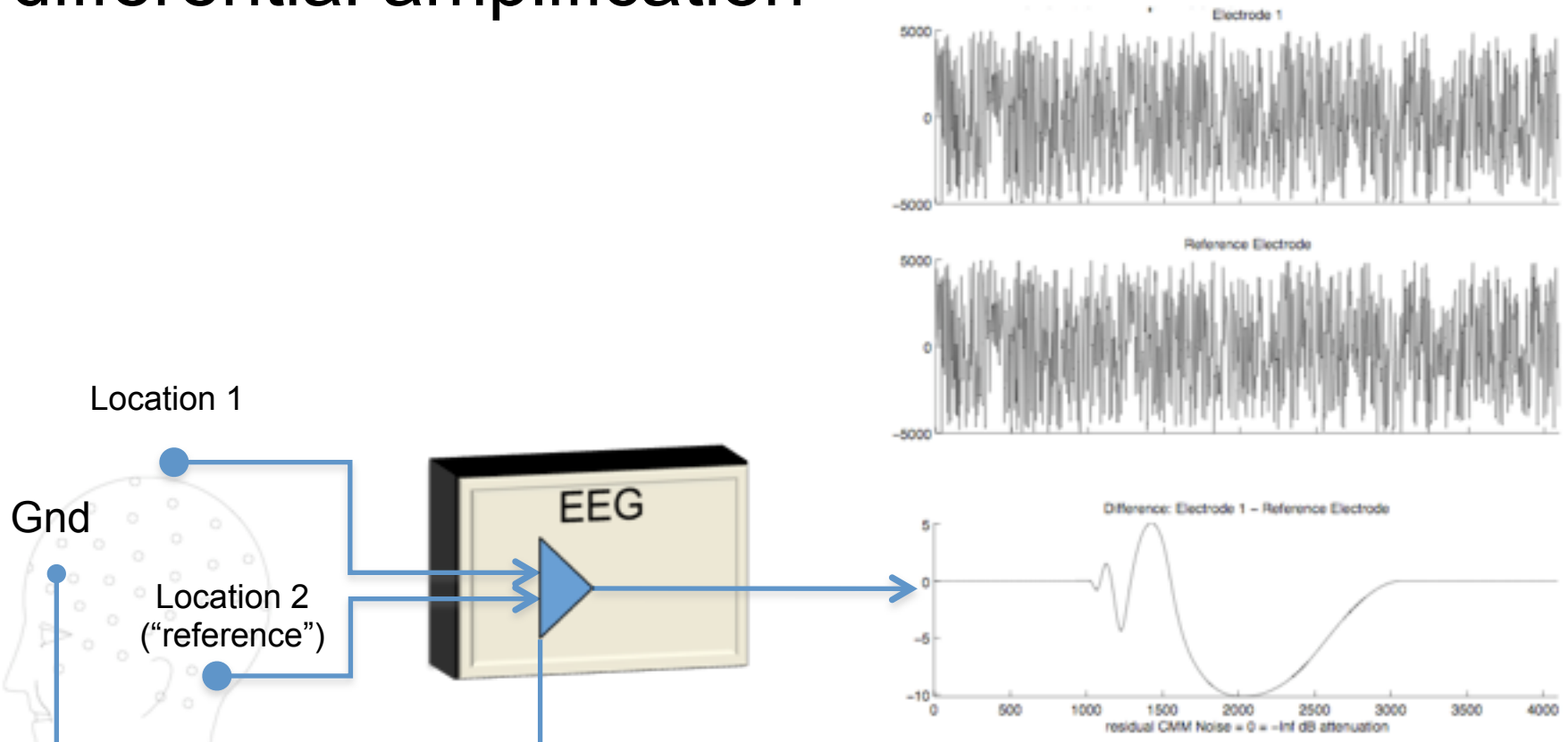
Analog to Digital Converter

Multichannel EEG

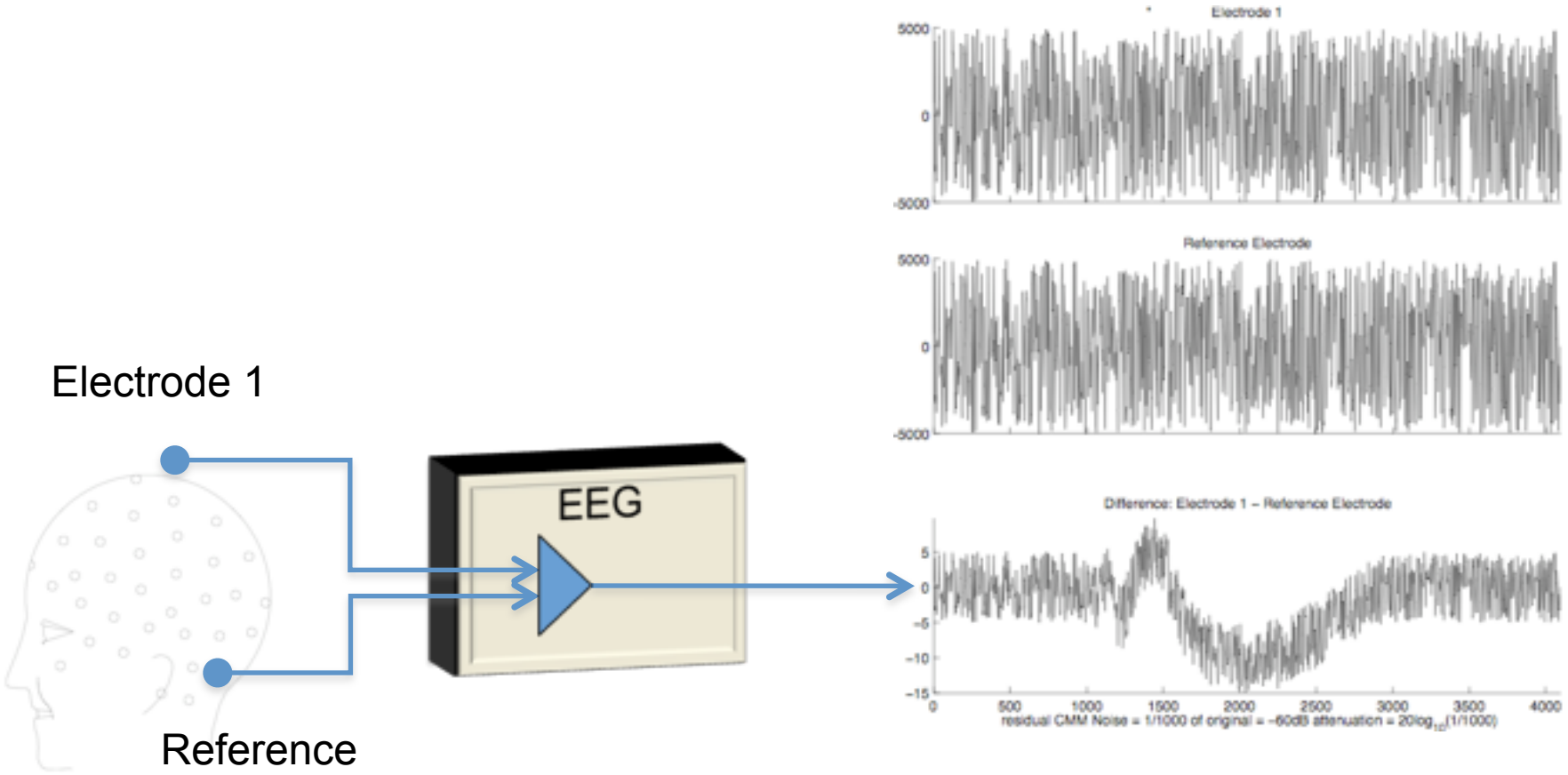



**Electrodes**
material
montage
reference

# Common mode noise and reduction by differential amplification

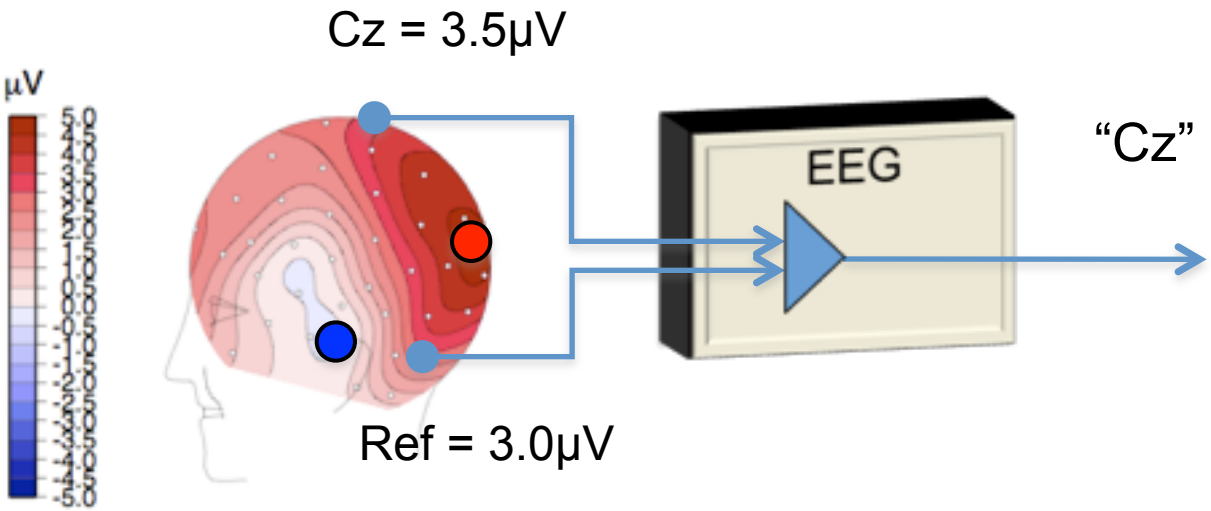


# Reduction is not elimination …




Ability to reject common mode noise is an important design specification of amplifier

# Differential amplification is *differential*




"Cz" amp output is ***really*** a difference: Cz-Ref

"Cz" amp output ***depends*** on reference location

"Cz" = Cz - ● = 3.5 – 5.0 = **-1.5μV**

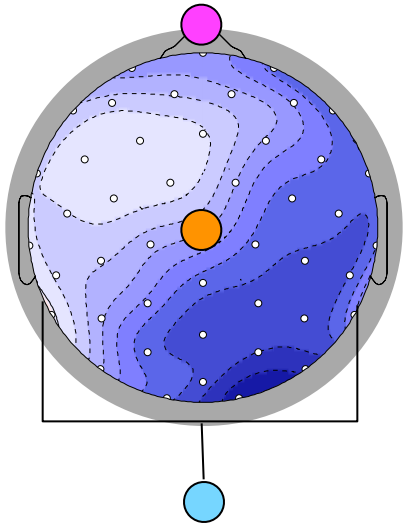
"Cz" = Cz - ● = 3.5 – (-0.5) = **4.0μV**

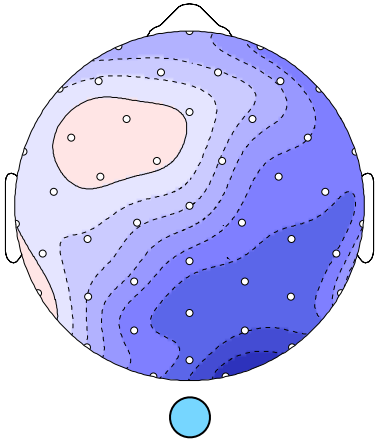
# There is no (reference) free lunch ...

- **Common reference** $=_{df}$ one reference for all locations
  - **Single**: left mastoid, left earlobe, nose tip, vertex.
  - **Pairs**: linked mastoid, earlobes, sterno-vertabral
  - **Average**: average of all locations
- **Bipolar**: different pairs (no reference in common)
- "**Reference free**": e.g., average of all (common average) or subset of nearest neighbors (c.f. current source density)

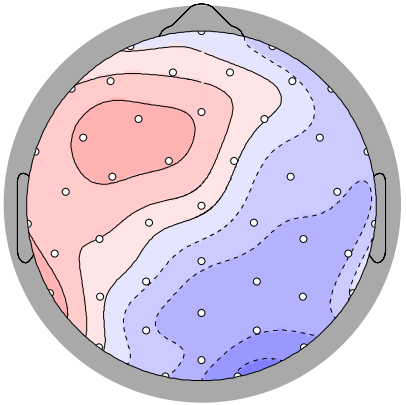
# Different references give different looking fields ...

"true" potentials
(-1.72 to 1.96uV)

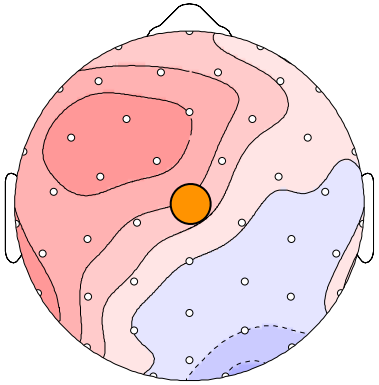




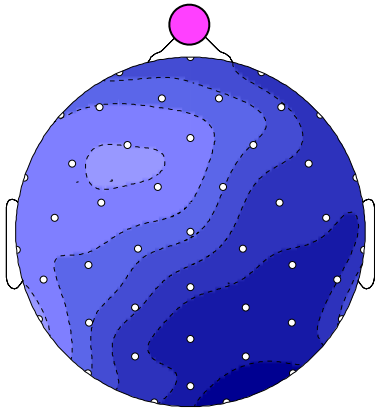
linked mastoid
(-1.59 to 2.09uV)



average
(-1.09 to 2.58uV)



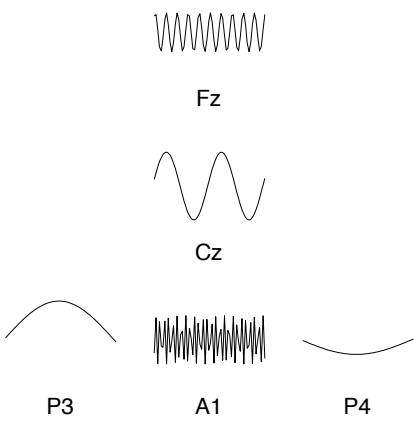
vertex
(-0.65 to 3.03uV)



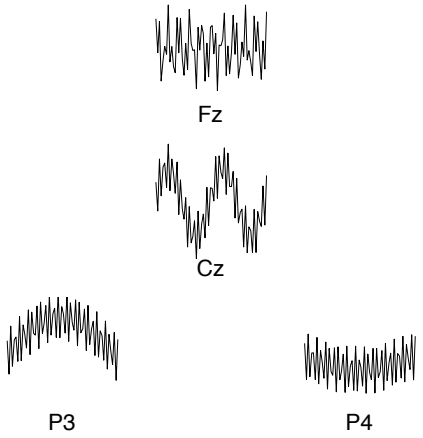
nose tip
(-2.80 to 0.87uV)

# And different looking time courses ...

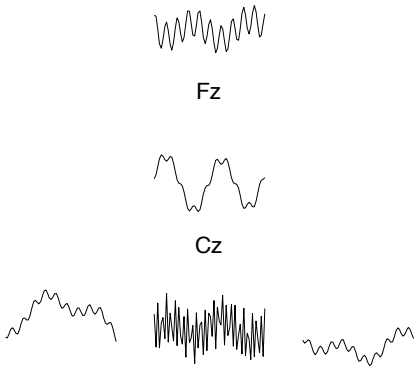
A) "true" potentials relative to infinitely distant reference



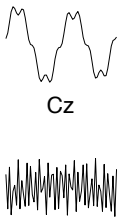

B) potentials relative to A1 reference



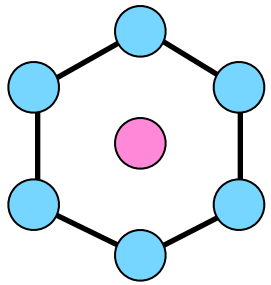

C) potentials relative to average reference



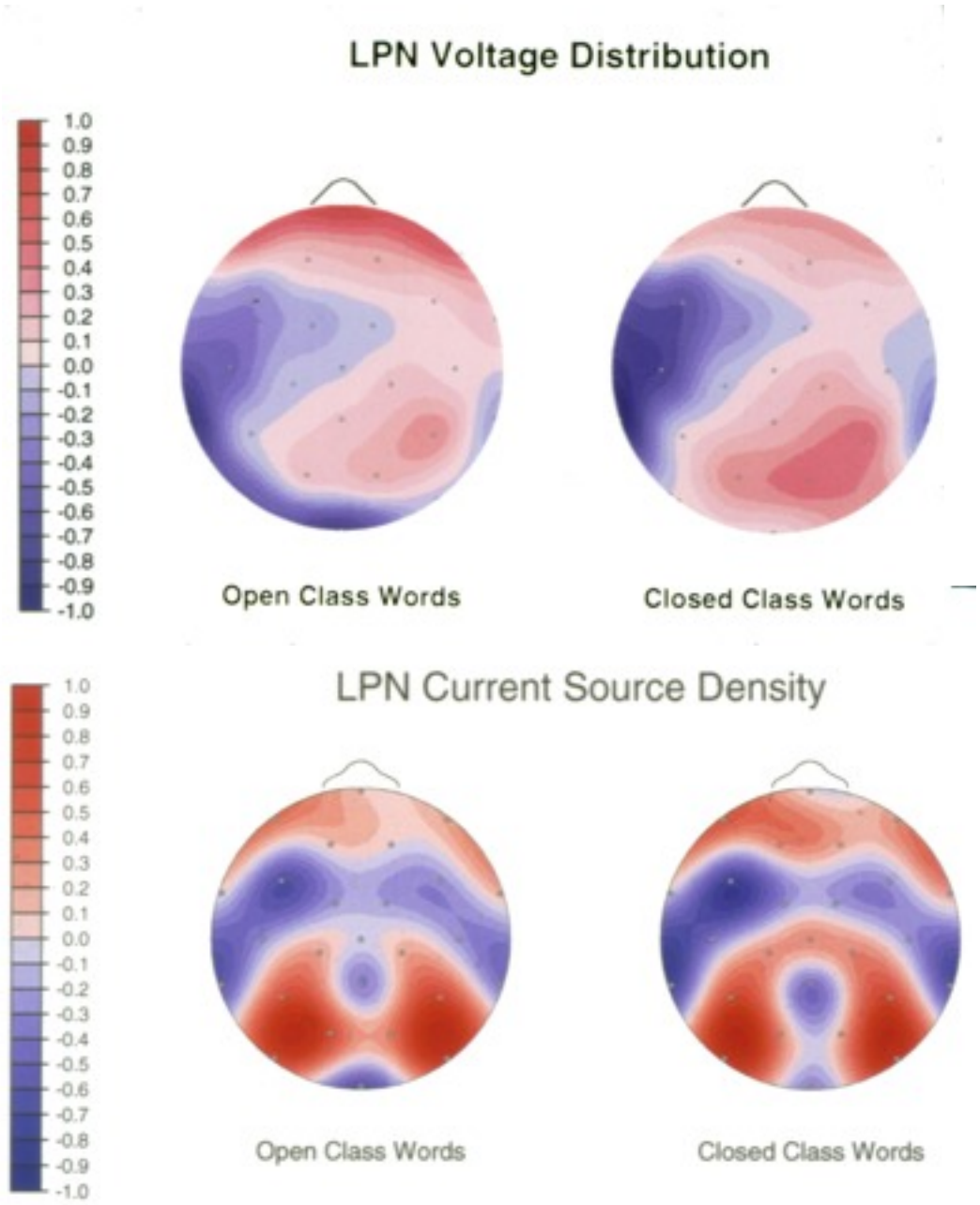

D) potential at Cz relative to average of three nearest neighbors



# Nearest neighbor reference

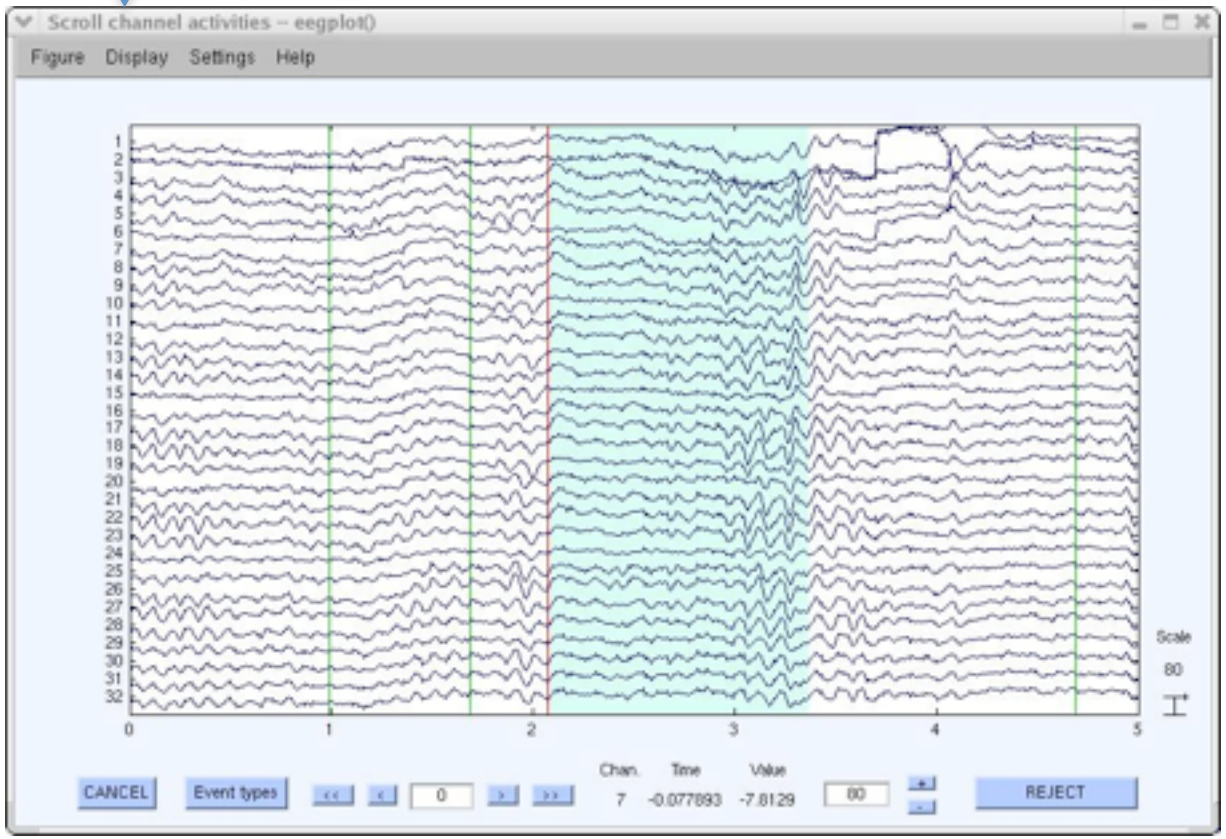


Current Source Density



**Digitization**
sampling rate
**bits per sample**

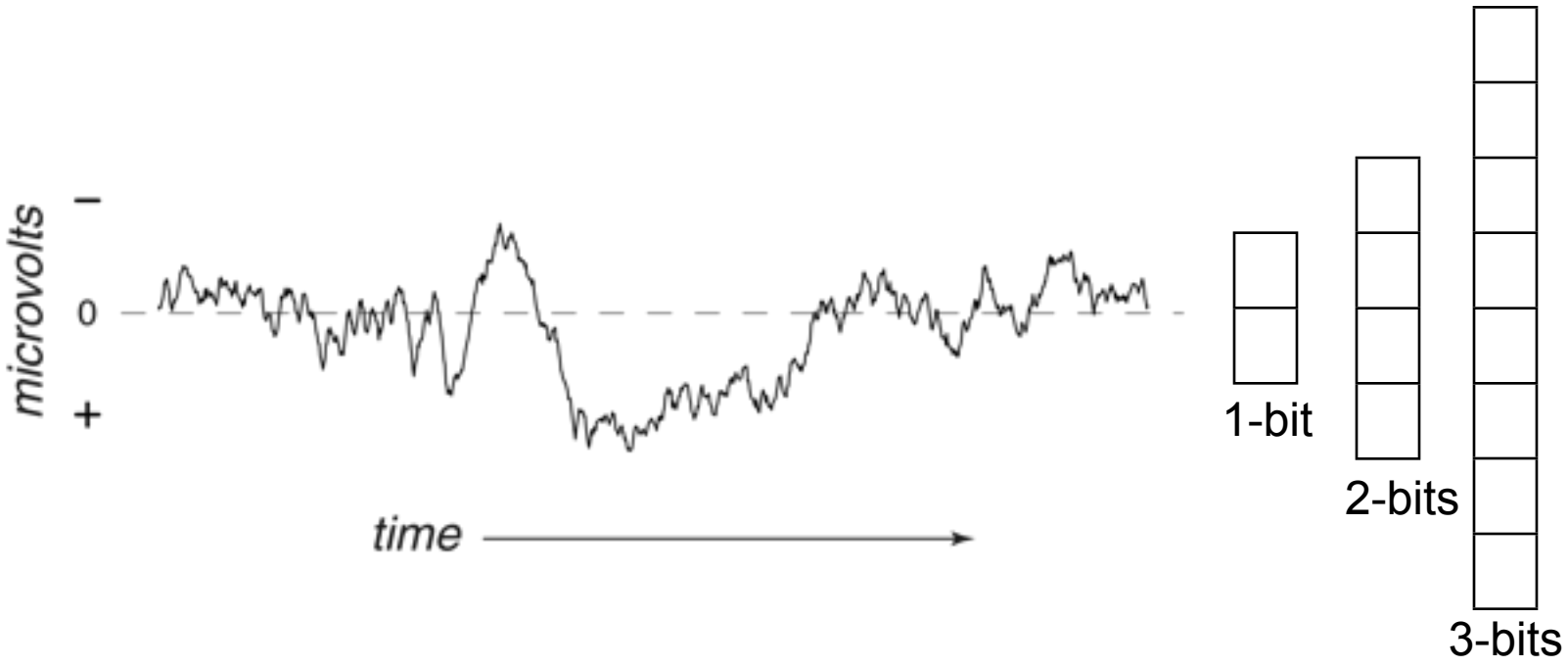
**Differential amplification**
**gain**
high pass filter
low pass filter



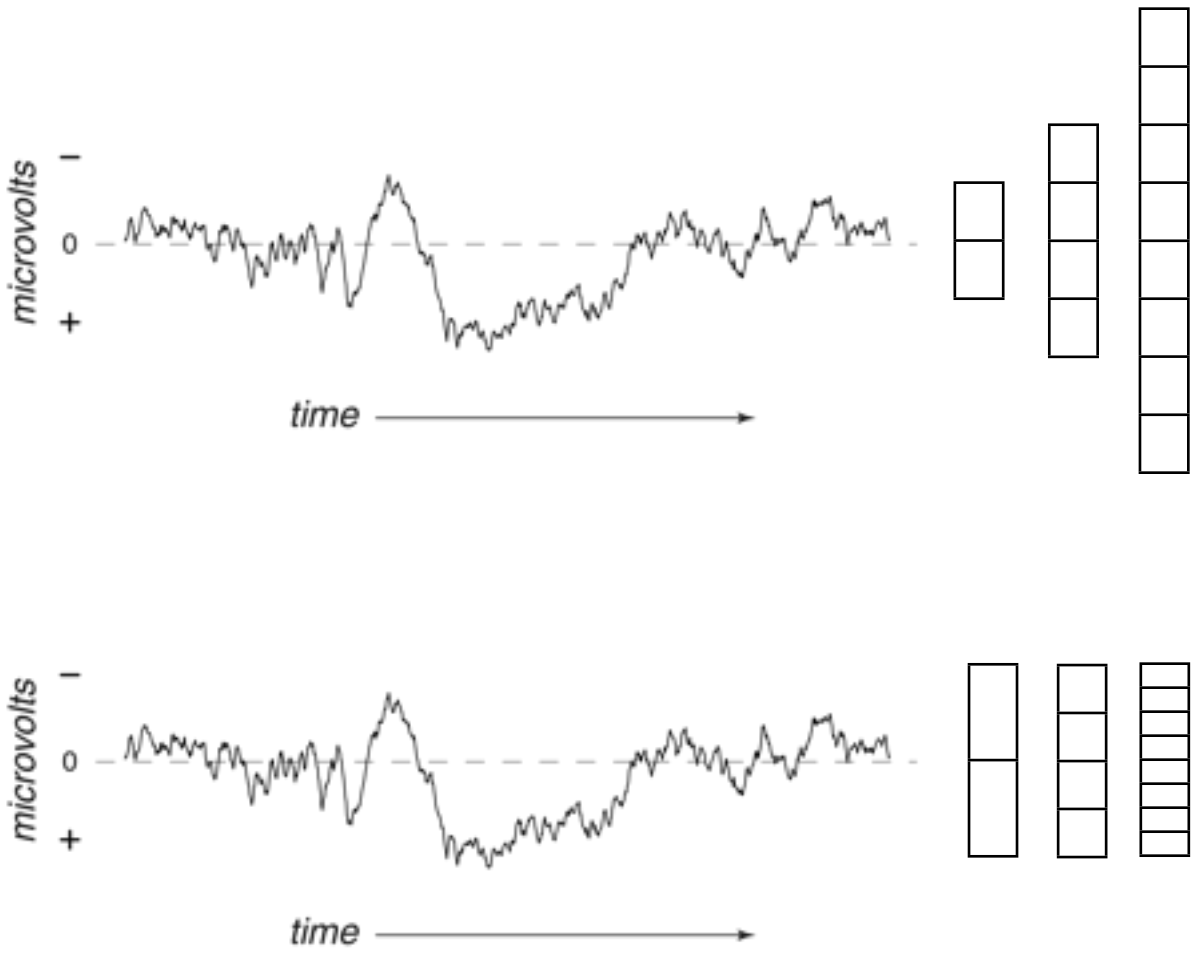
# Digital sampling: bits

Continuous voltage is encoded as one of a set of integer value

| *n* of Bits | $2^n$ of Values |
|---|---|
| 2 | 4 |
| 8 | 256 |
| 12 | 4096 |

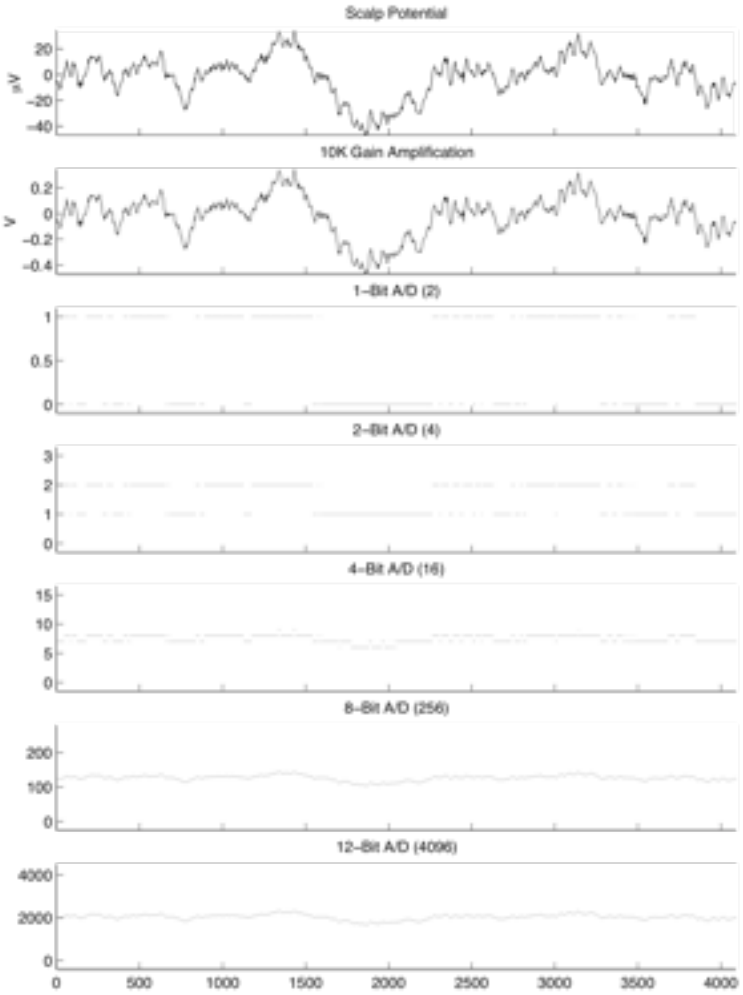


# Trade-off: dynamic range vs. resolution

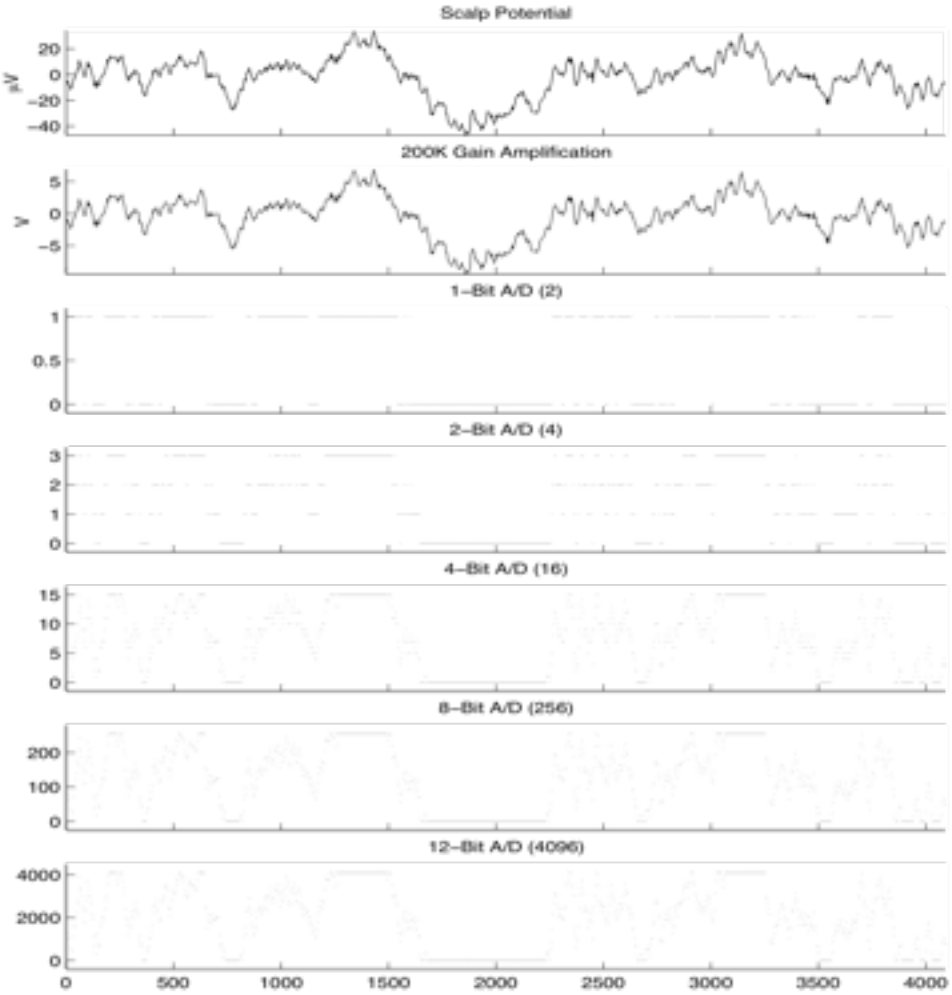


# Digital sampling: bits vs. amplifier gain

Gain Too Low

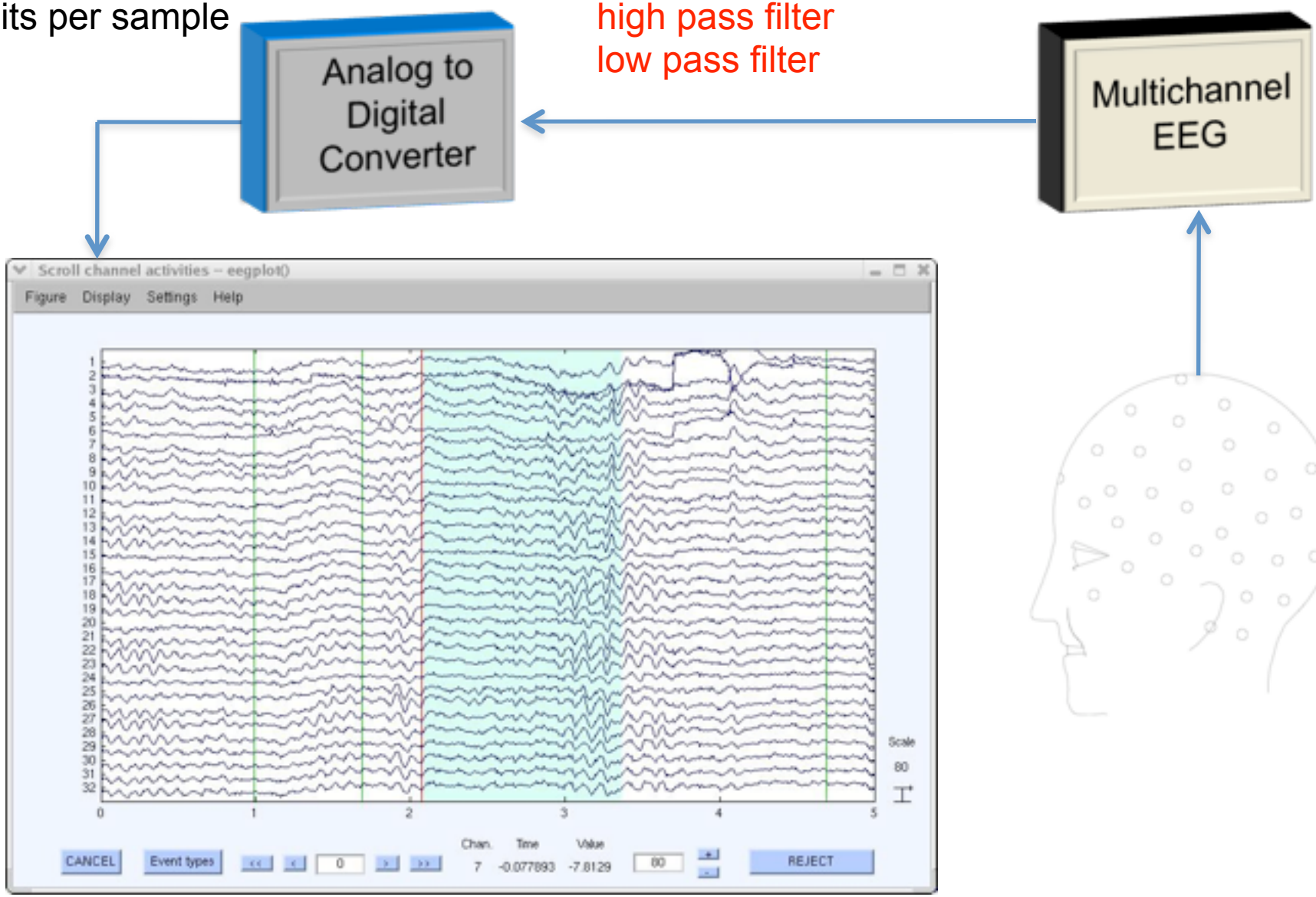



Gain Too High

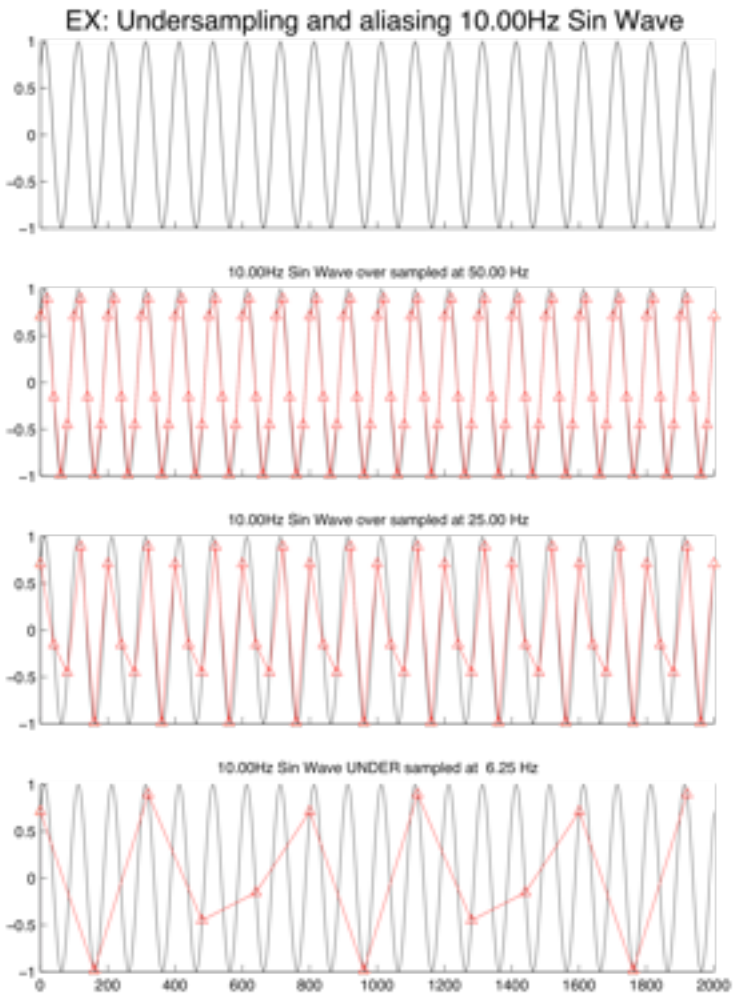


**Digitization**
sampling rate
bits per sample

**Differential amplification**
gain
high pass filter
low pass filter



# Digital sampling: what rate?




Theoretically twice the highest frequency in the data (Nyquist)

In practice oversampling at 2.5 – 5x is common

So what is the “highest frequency” in EEG data …

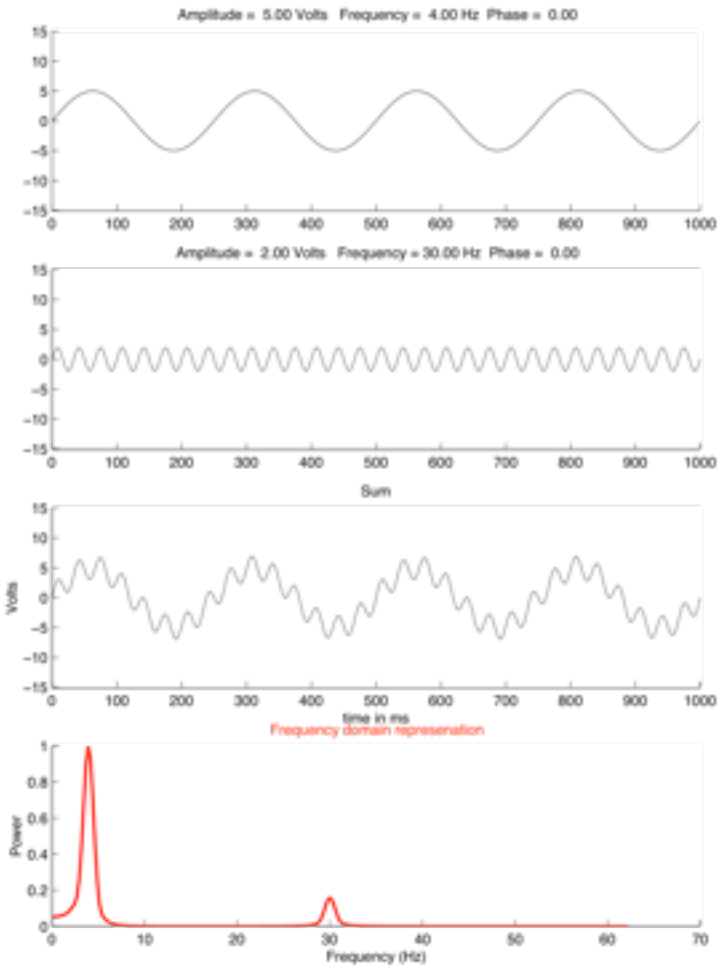
# Highest frequency in EEG depends …

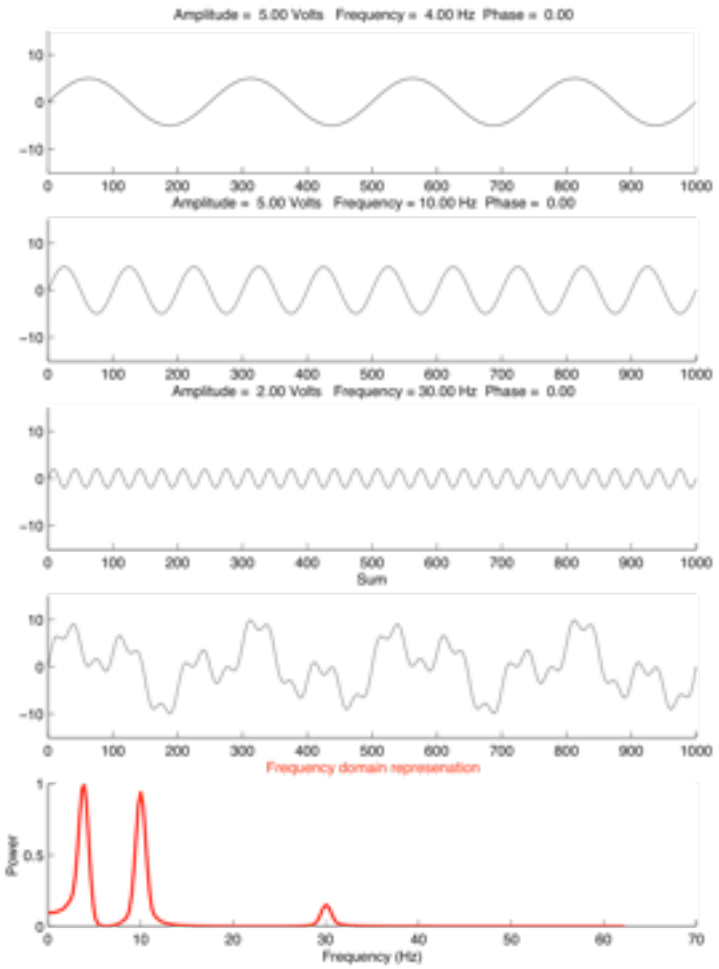
- Brainstem potentials … ~ 500Hz
- EEG < 100Hz
- Cognitive ERPs < 30Hz

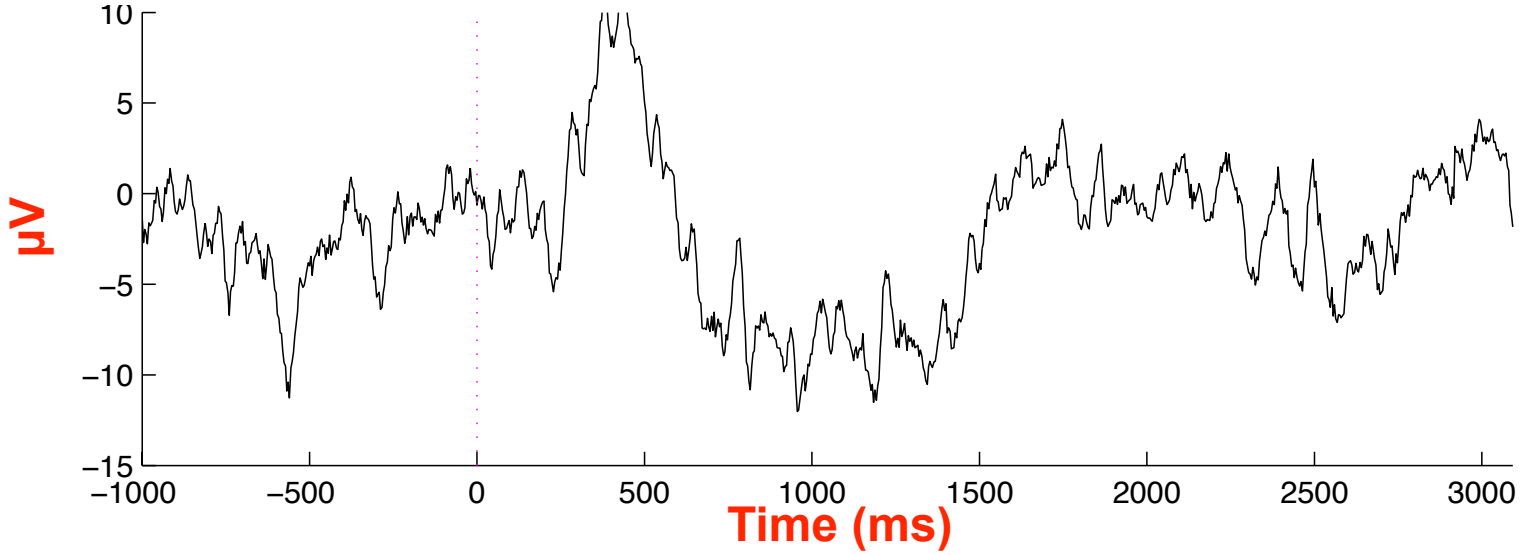
- Necessary to filter out high frequencies with a low pass filter before digitizing data to ensure that sampling rate is at least 2x as high as highest frequency in the signal.

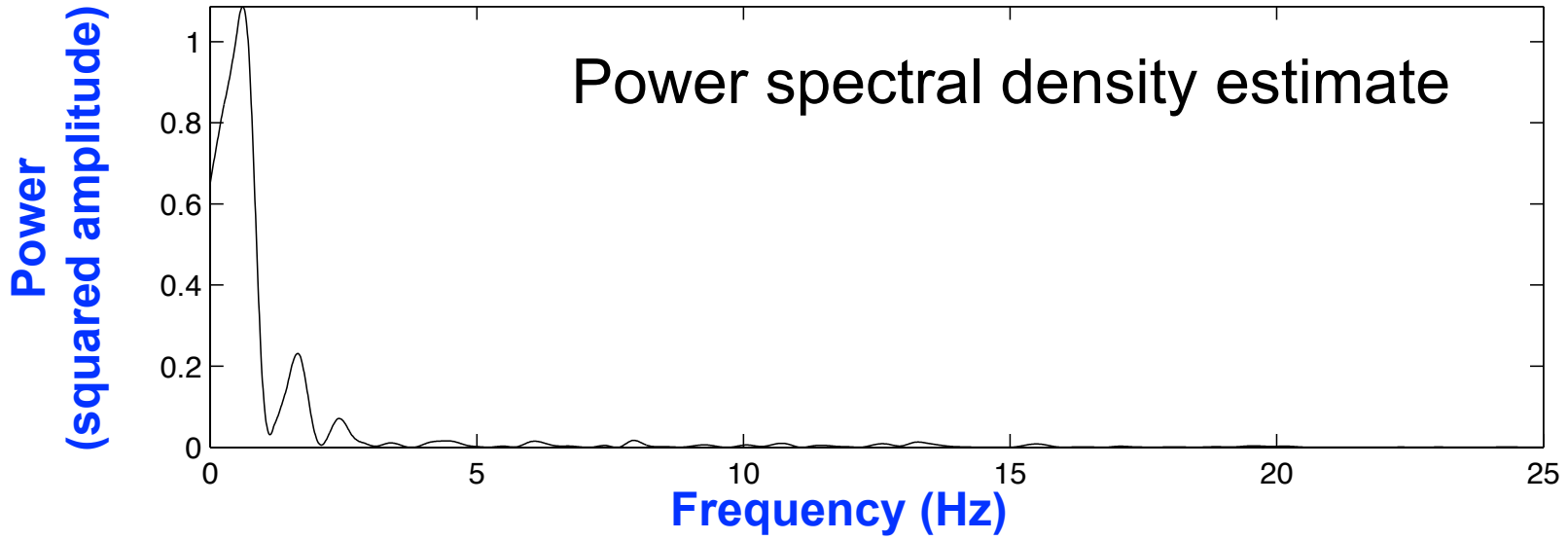
- Often necessary to filter out very low frequencies (0.01 Hz) so that slow non-neural electrical potentials do not go outside range of amplifier or ADC (analog to digital converter)

# Time vs. frequency representations




10
5
0
−5
−10
−15
μV
−1000
−500
0
500
1000
1500
2000
2500
3000
Time (ms)


Power spectral density estimate
Power
(squared amplitude)
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
Frequency (Hz)

# Filter Terminology: filters as sieves

**Low pass filters** – attenuate high frequencies and pass low frequencies

**High pass filters** – attenuate low frequencies and pass high frequencies

**Bandpass filters** – attenuate high and low frequencies, pass intermediate frequencies

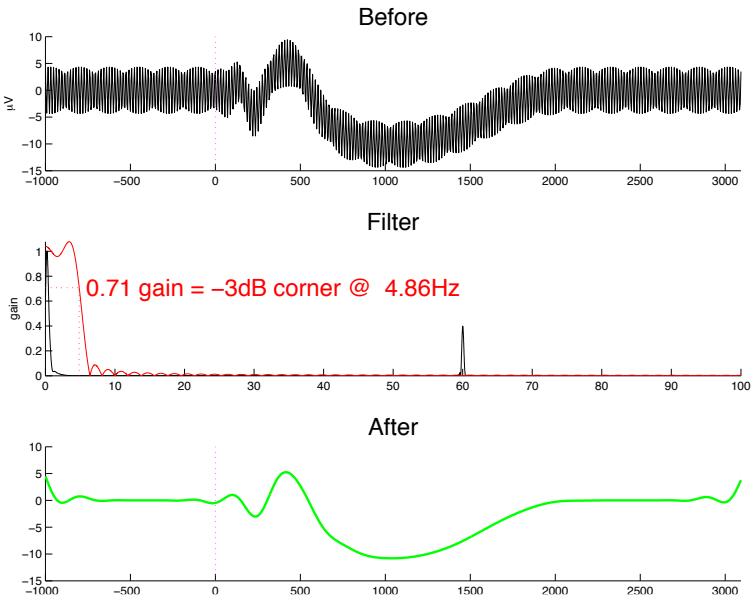
**Notch filters** – attenuate some narrow band of frequencies and pass all other frequencies

**Cutoff frequency** – the frequency $\boldsymbol{f_c}$ (Hz) at which the filter's output is reduced to .71 = 1/(sqrt(2) = 3 dB of its input. aka 3dB corner frequency.

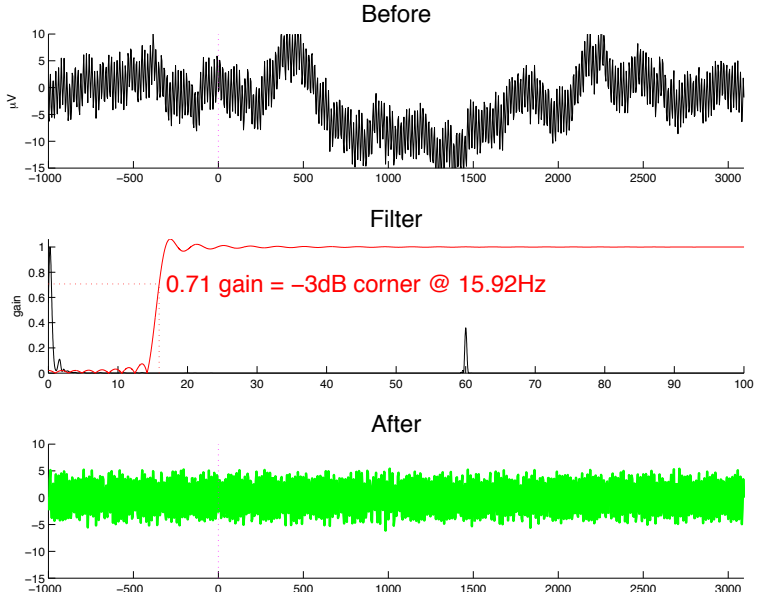
**Rolloff** – rate at which attentuation changes with frequency (dB/octative)

**High pass filter *time constant*** – alternative expression for the cutoff frequency, expressed in seconds: the time constant $\tau = 1/(2\pi \boldsymbol{f_c})$

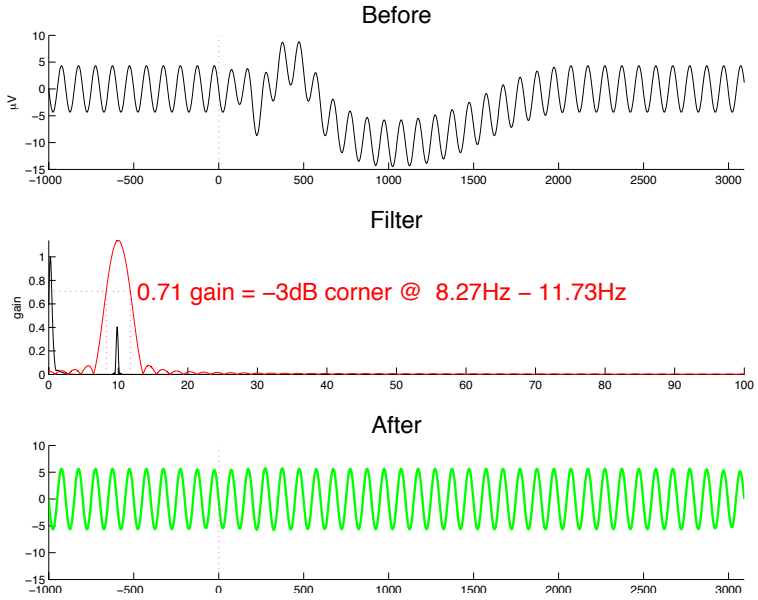
# Low pass 4.9 Hz



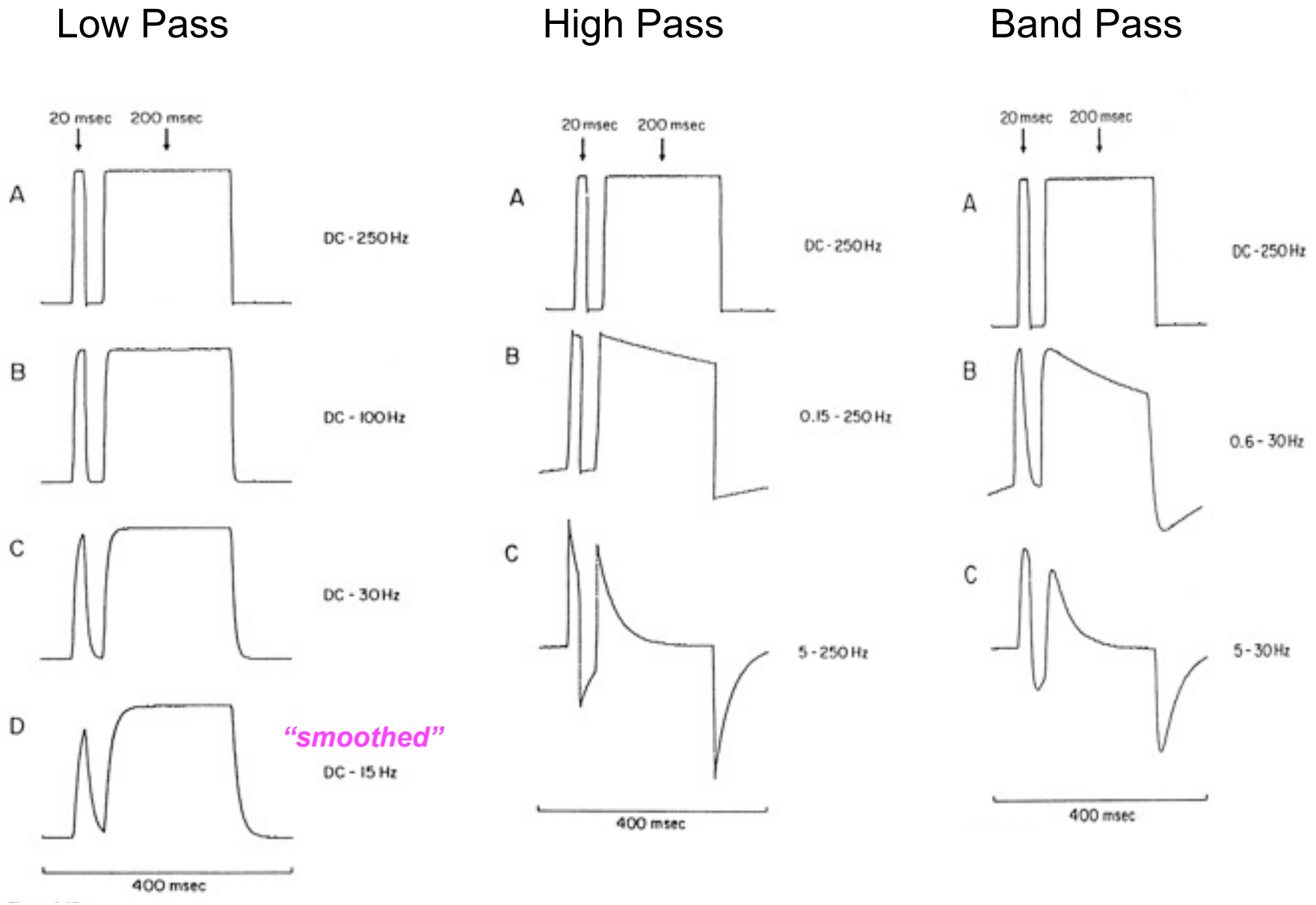

# High pass 15.9 Hz



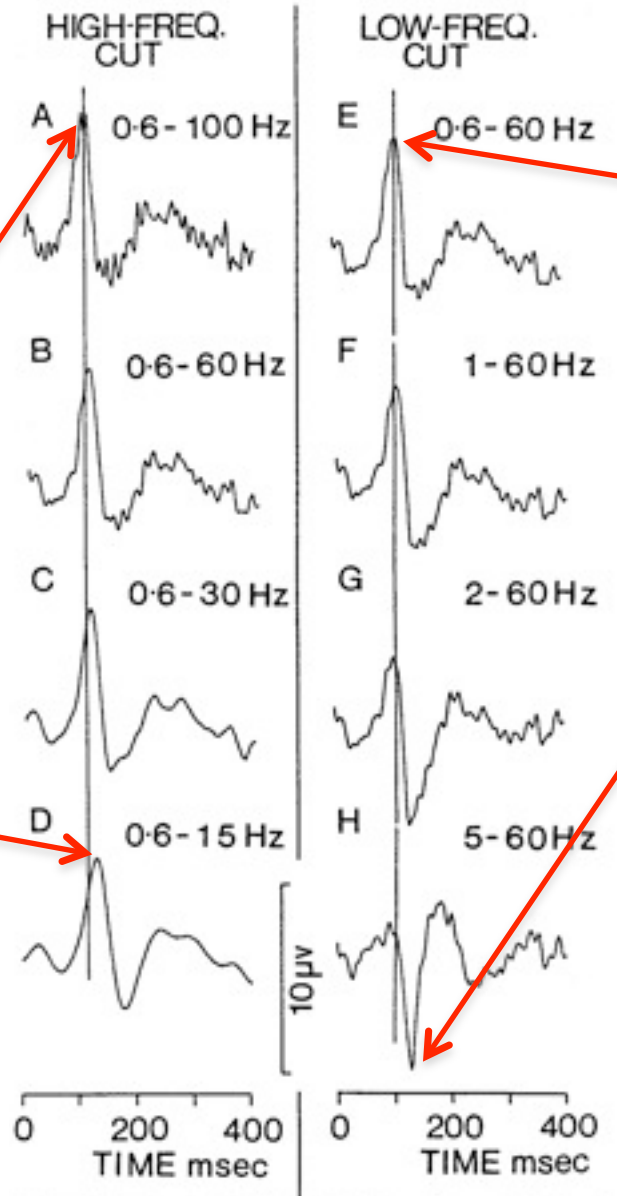

# Band pass 8.3 - 11.7Hz



# Filtered = distorted, perhaps for the good. Maybe not.

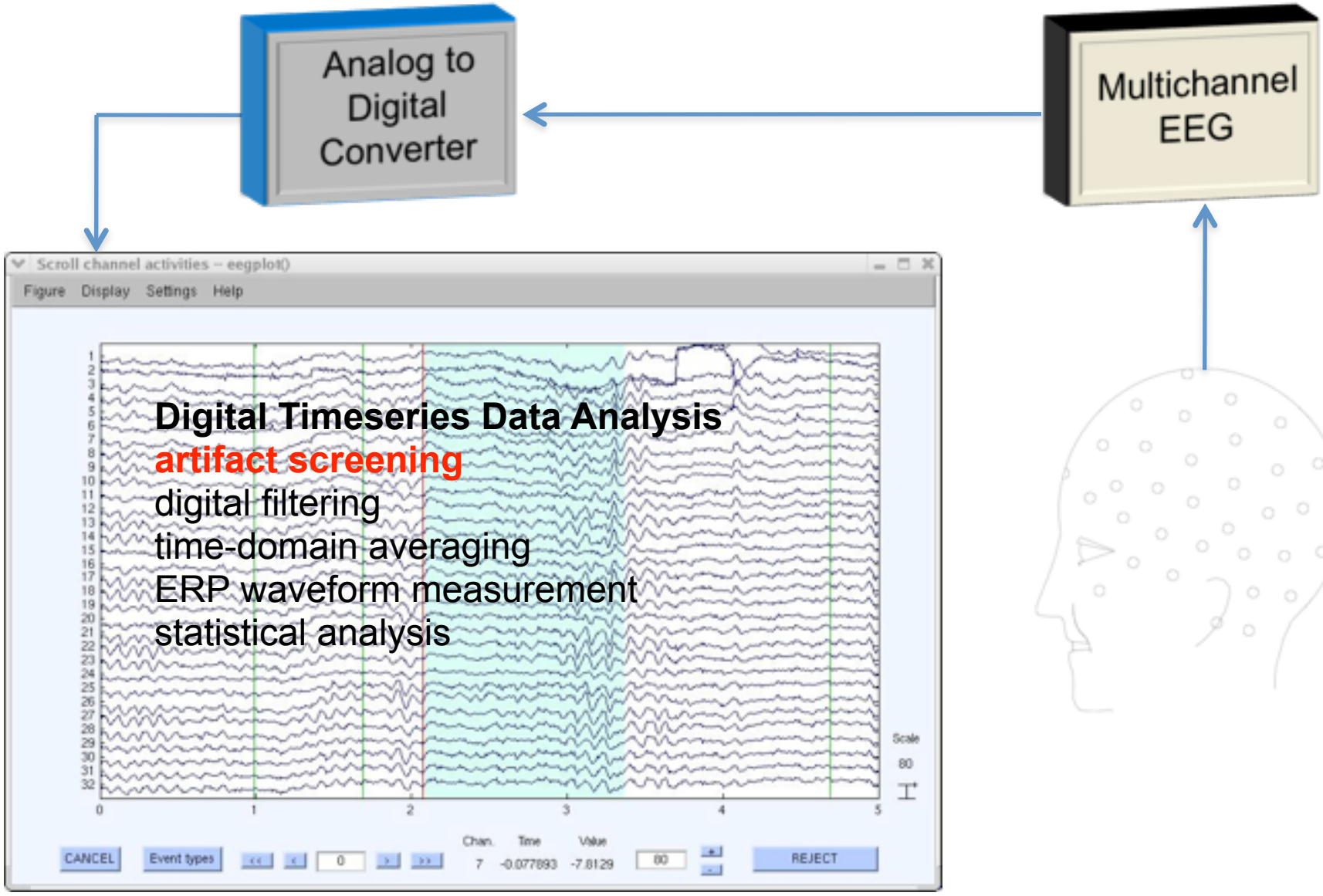


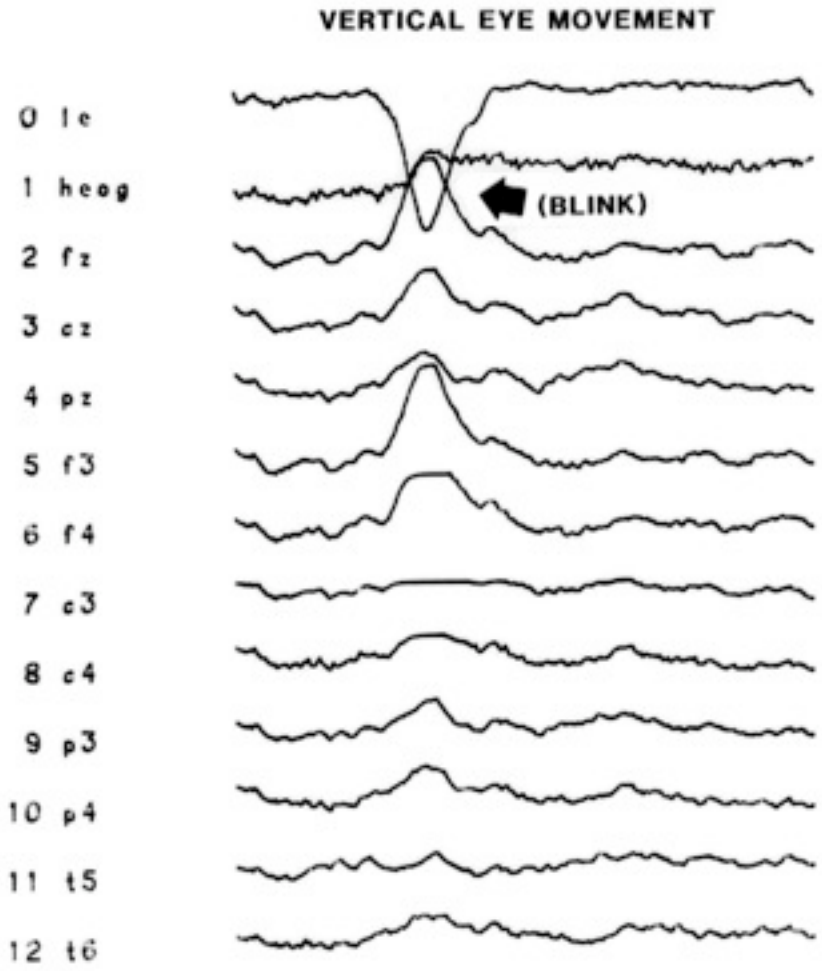
# Same goes for filtered ERPs



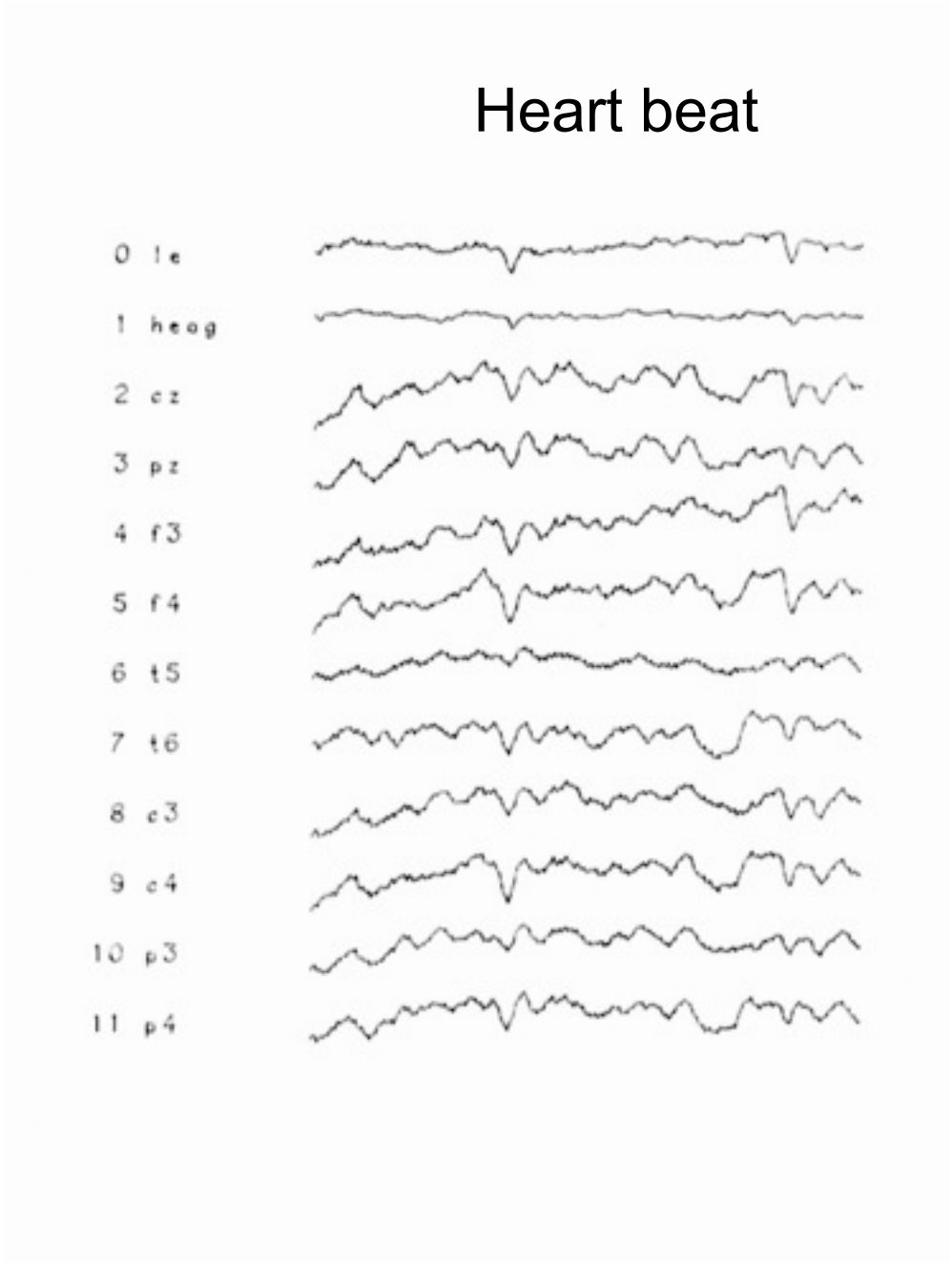

peak shifts
in time
(analog filter)

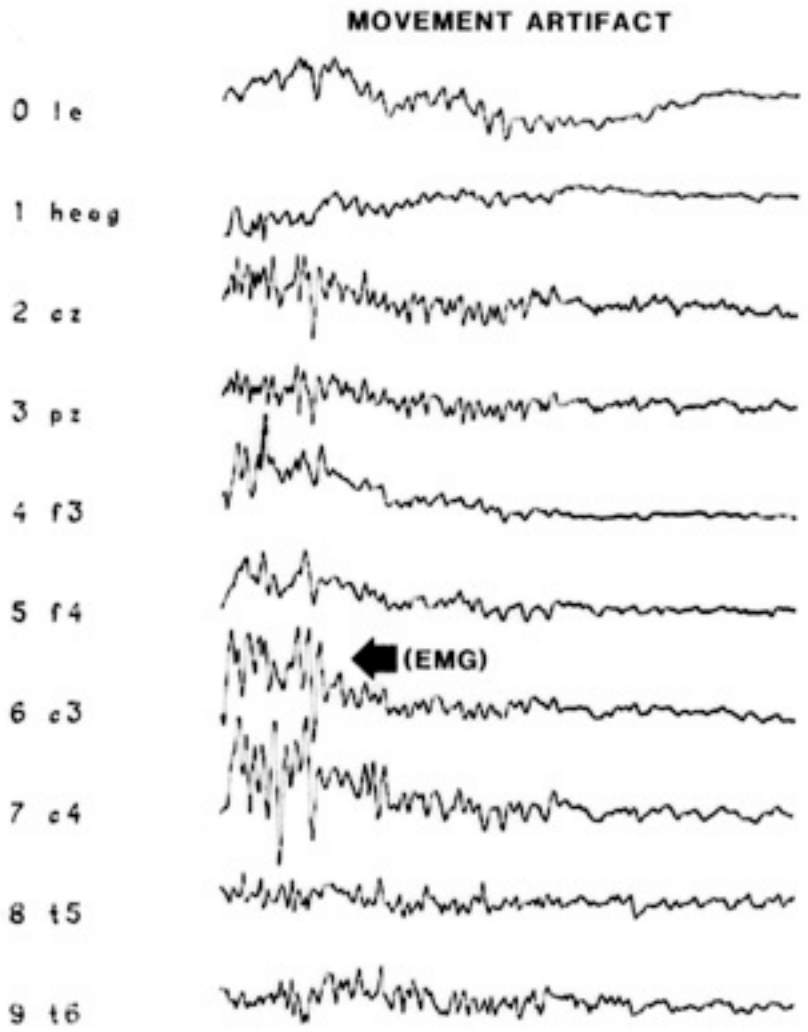
peak shifts
polarity


Analog to Digital Converter
Multichannel EEG
Scroll channel activities – eegplot()
Figure Display Settings Help
Digital Timeseries Data Analysis
artifact screening
digital filtering
time-domain averaging
ERP waveform measurement
statistical analysis
Scale
80
Chan. Time Value
7 -0.077893 -7.8129
CANCEL
Event types
REJECT


VERTICAL EYE MOVEMENT
0 le
1 heog
2 fz
3 cz
4 pz
5 f3
6 f4
7 c3
8 c4
9 p3
10 p4
11 t5
12 t6
(BLINK)

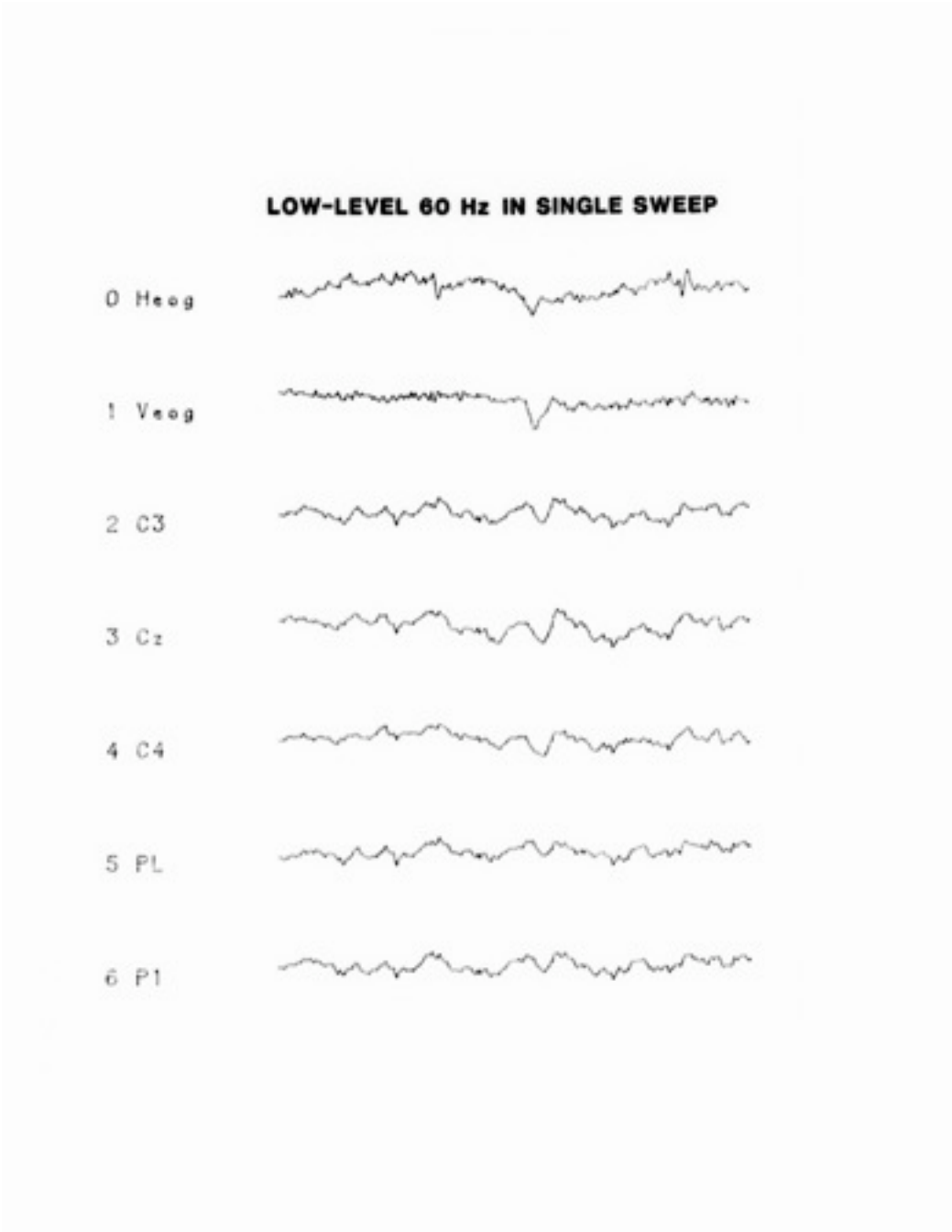
# Heart beat

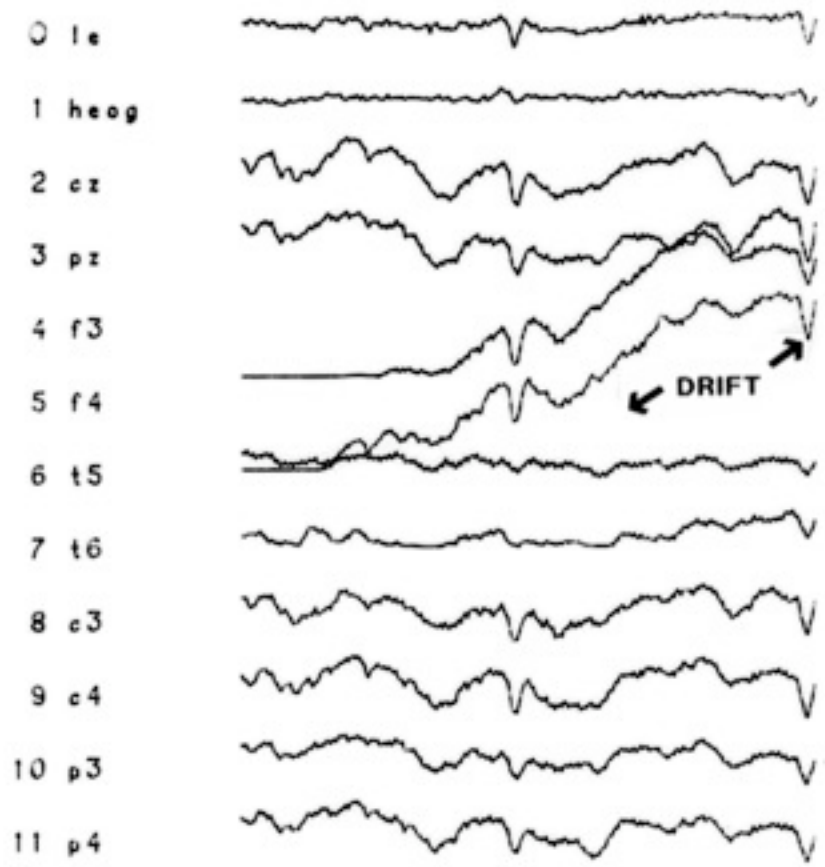


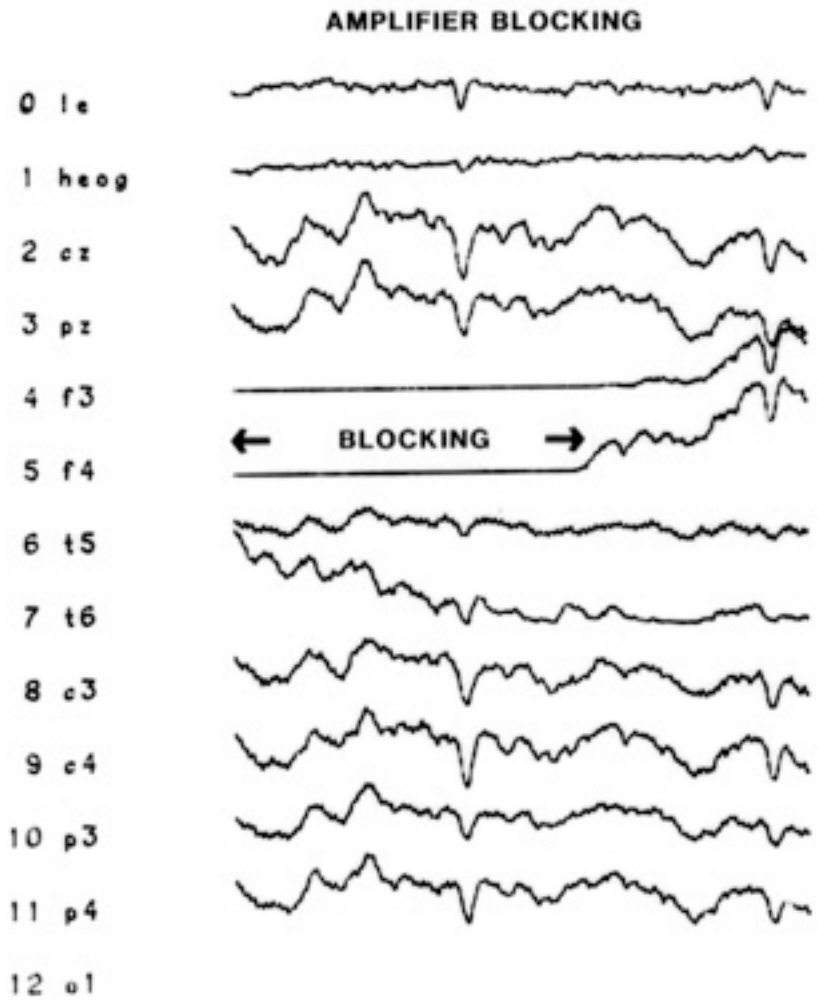

MOVEMENT ARTIFACT
0 le
1 heog
2 cz
3 pz
4 f3
5 f4
(EMG)
6 c3
7 c4
8 t5
9 t6

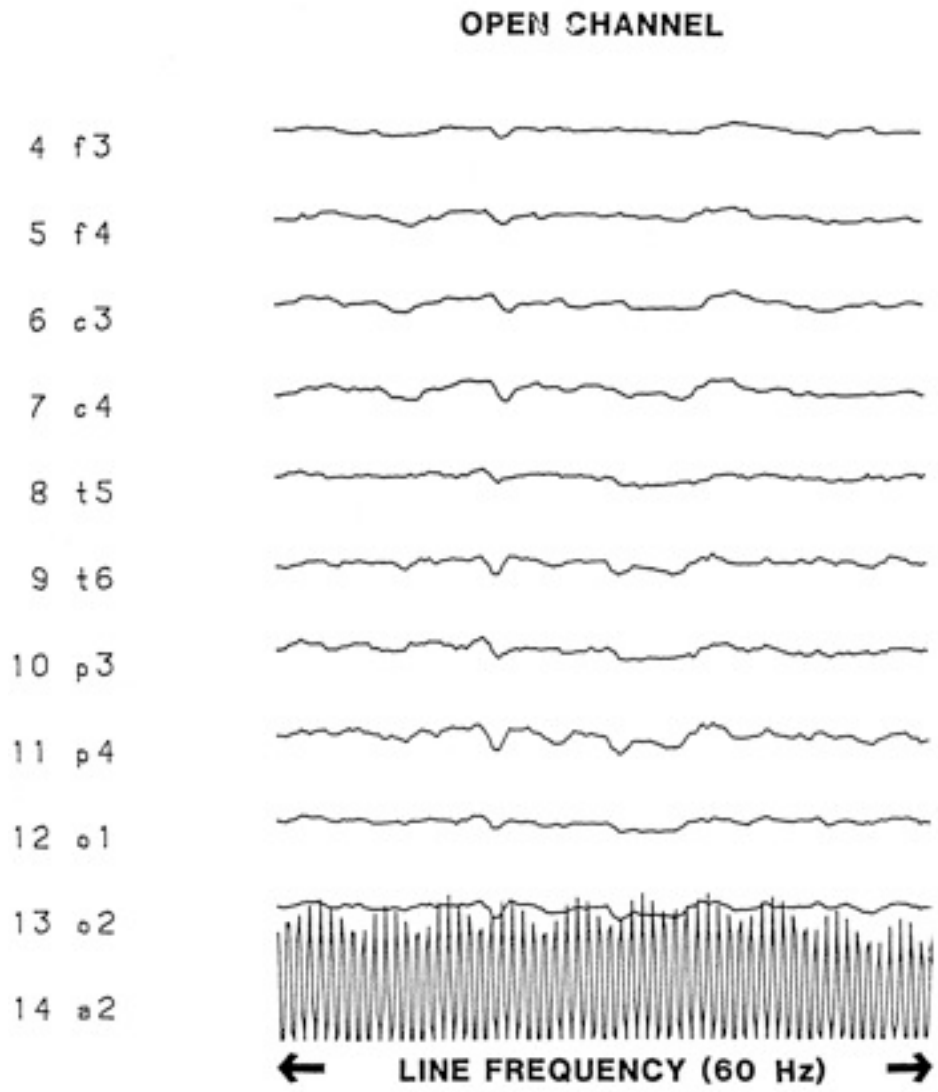
Electrical noise

- AC line current (60 Hz)
- video monitors (50-120 Hz, refresh rate)

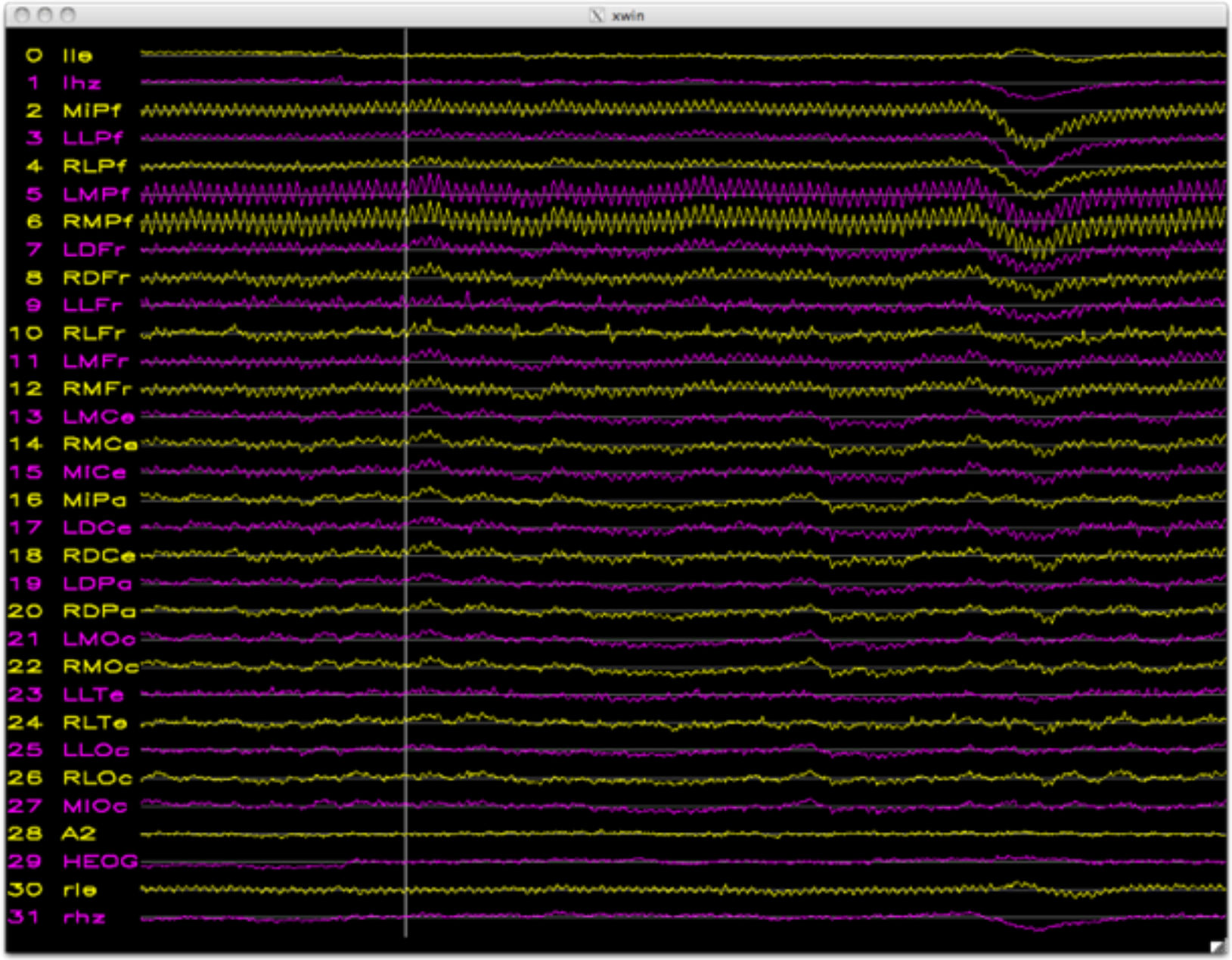



0 le
1 heog
2 cz
3 pz
4 f3
5 f4
6 t5
7 t6
8 c3
9 c4
10 p3
11 p4
DRIFT

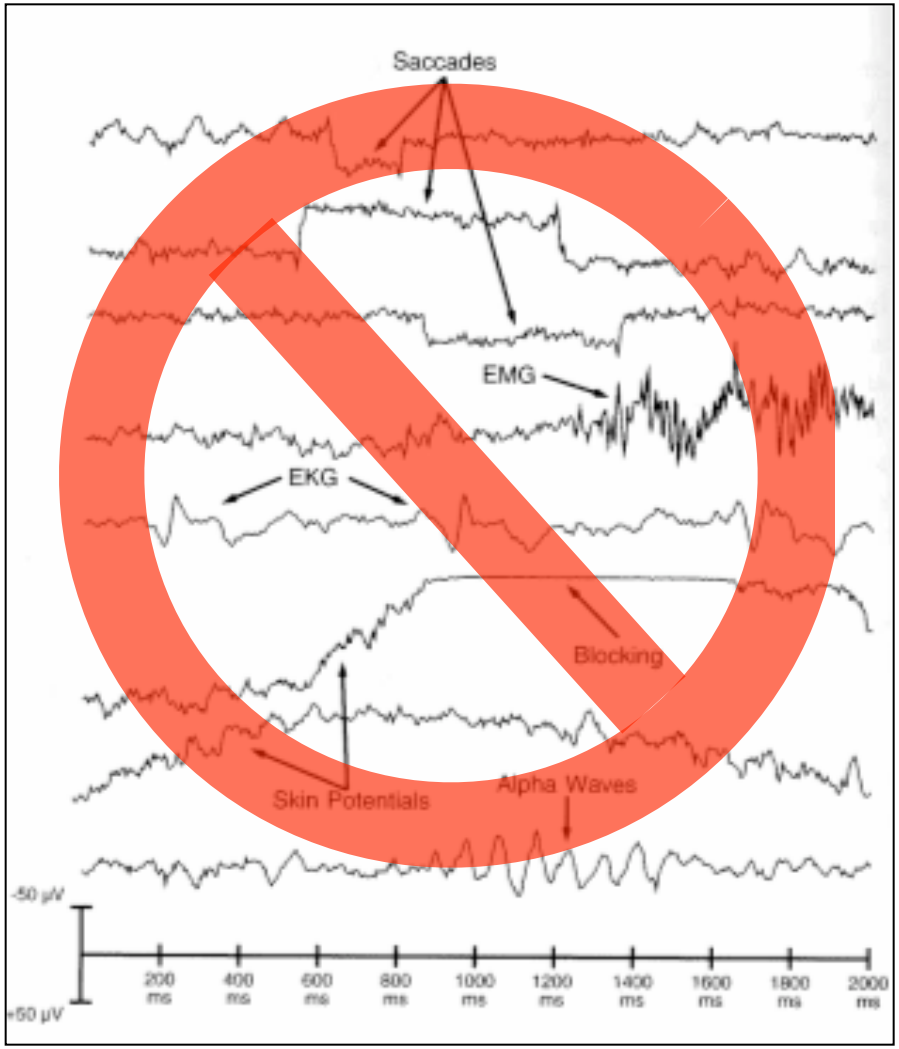

AMPLIFIER BLOCKING
0 le
1 heog
2 cz
3 pz
4 f3
BLOCKING
5 f4
6 t5
7 t6
8 c3
9 c4
10 p3
11 p4
12 o1


OPEN CHANNEL
4 f3
5 f4
6 c3
7 c4
8 t5
9 t6
10 p3
11 p4
12 o1
13 o2
14 a2
LINE FREQUENCY (60 Hz)

# EEG + 60 Hz & eye blink artifact

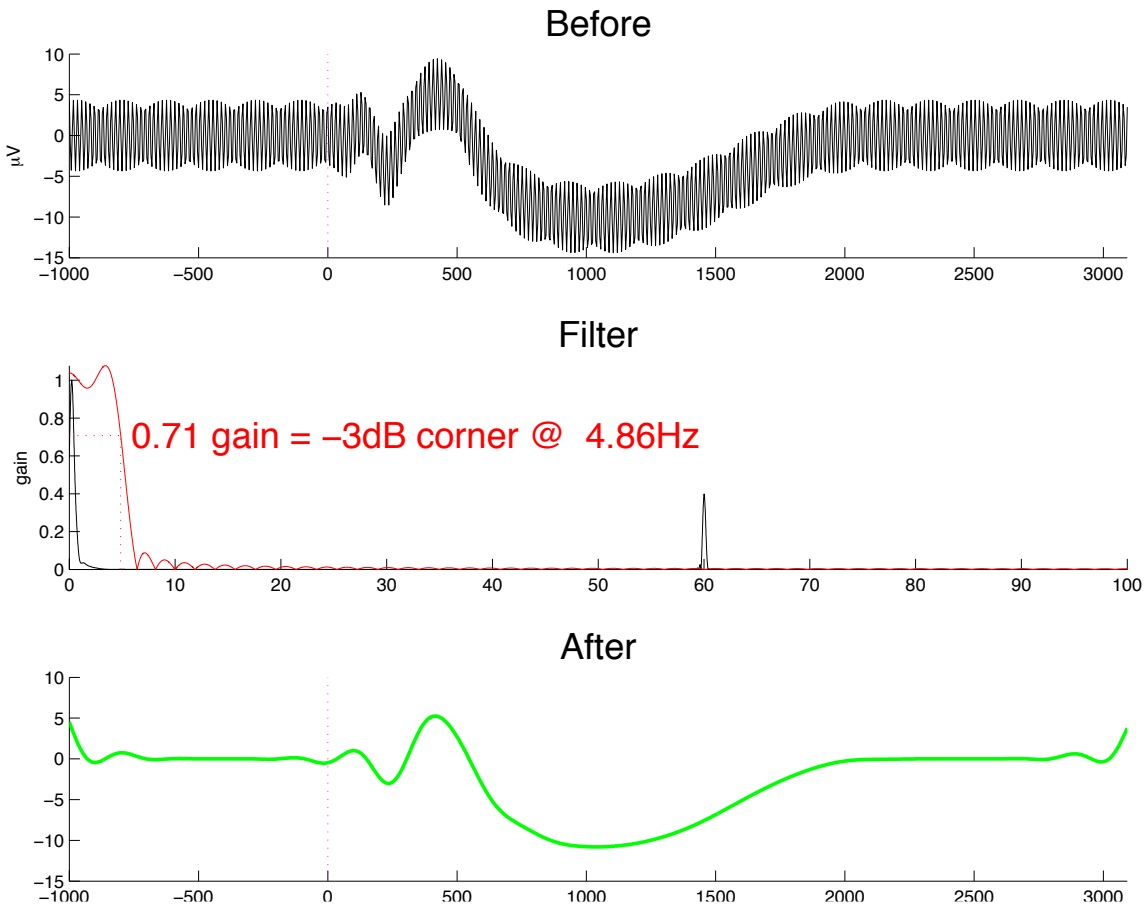


# Strategy 1: Exclude artifacts



# Strategy 2: Correct artifacts via decomposition/recomposition

## Example 1: frequency domain filtering




EEG + 60 Hz artifact

↓

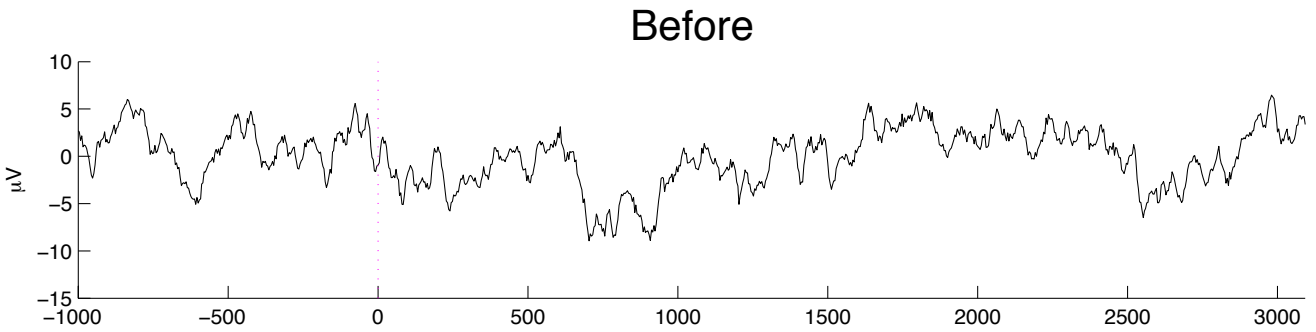
Frequency components

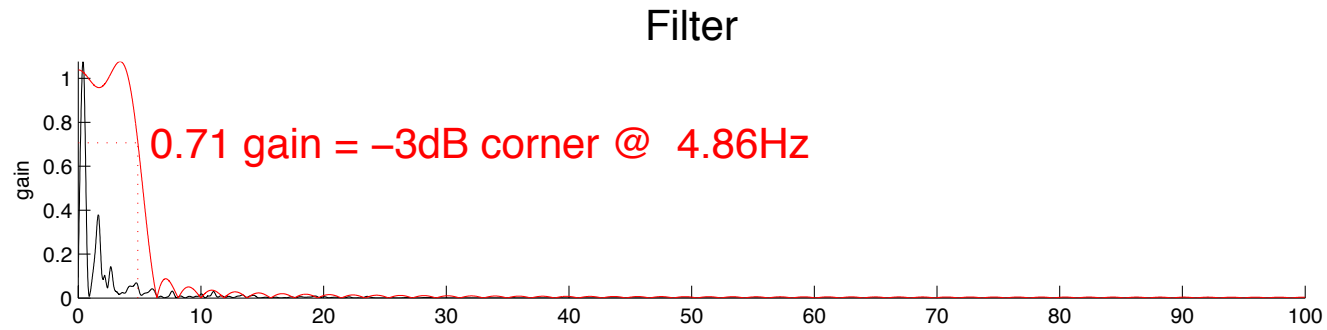
↓

Reconstruction from frequency components excluding 60 Hz

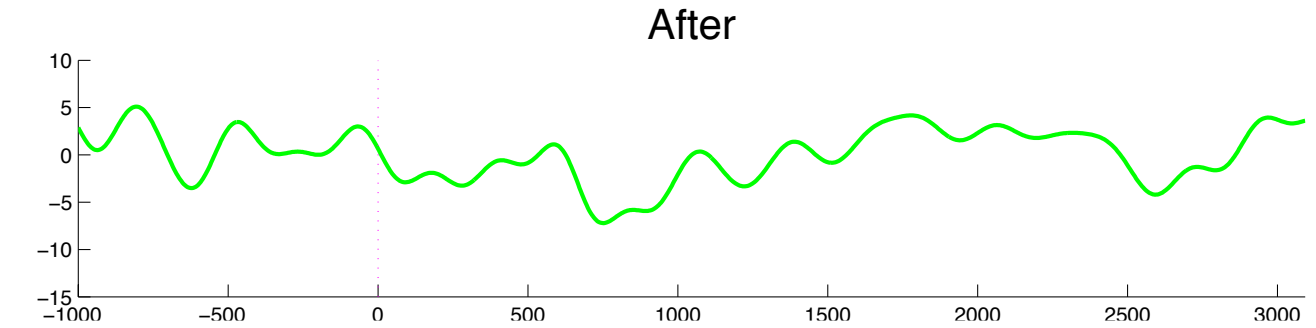
# *Filters do not turn lead into gold ...*

Mush

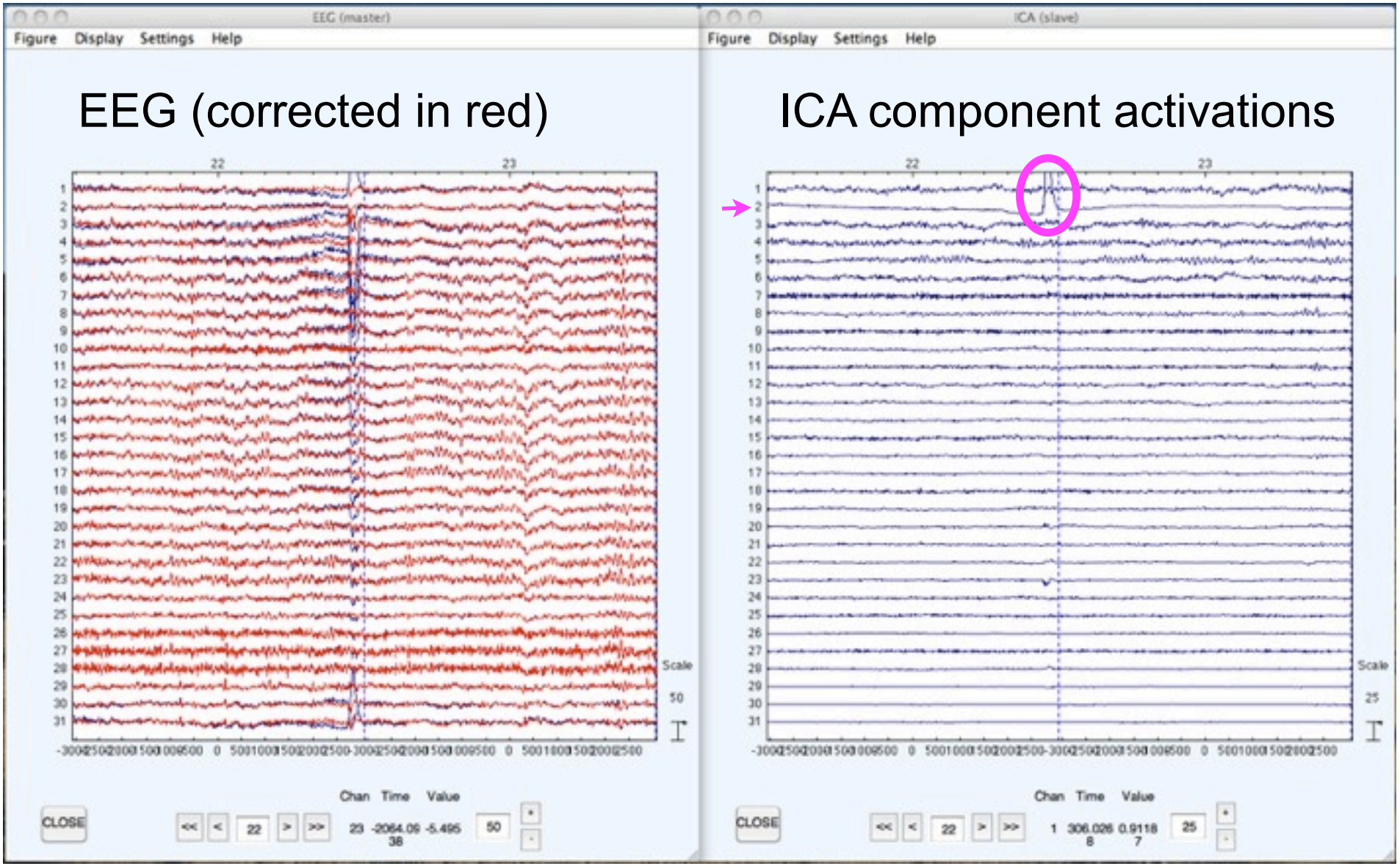


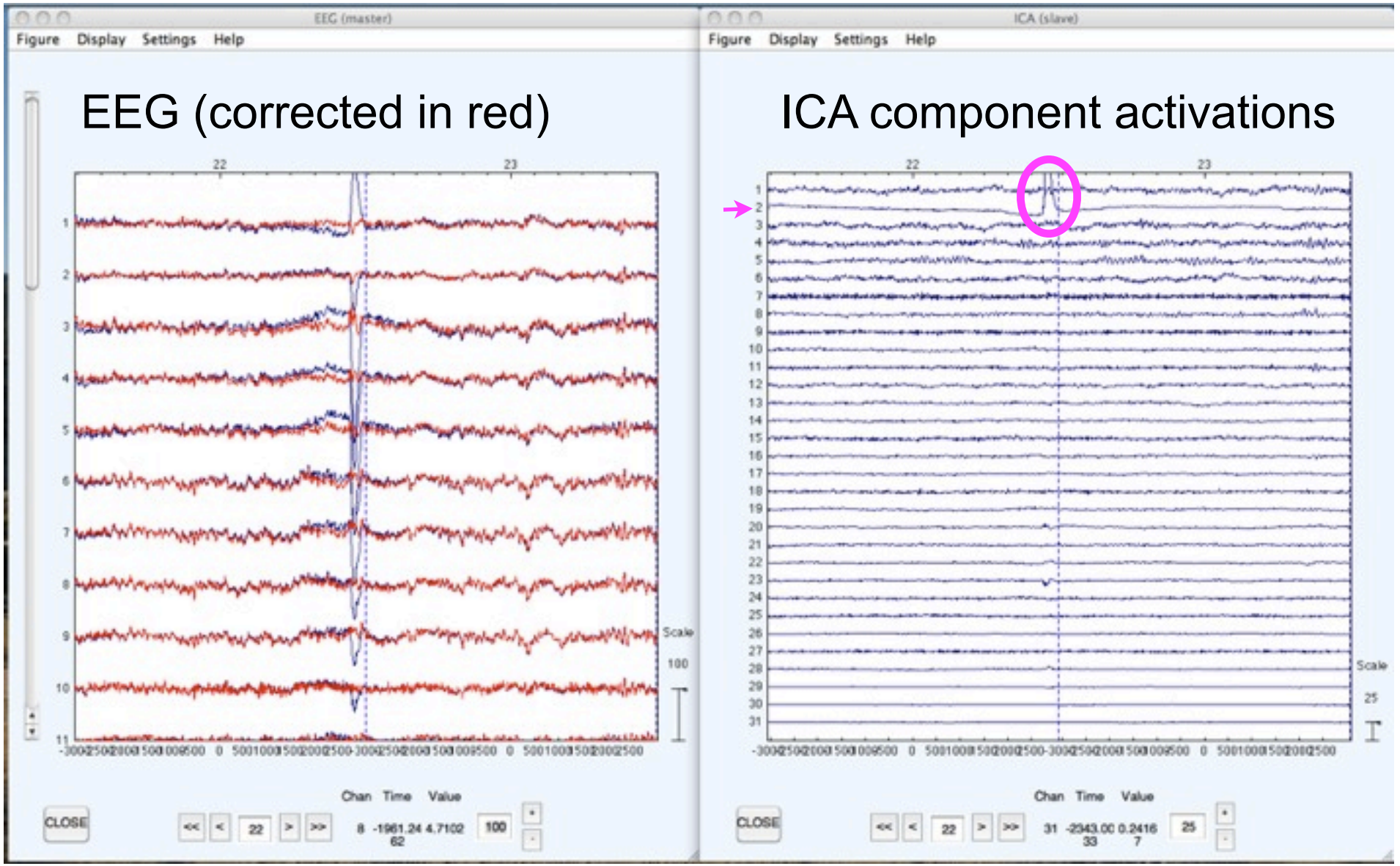

Smoother mush



# Example 2: ICA decomposition, recomposition

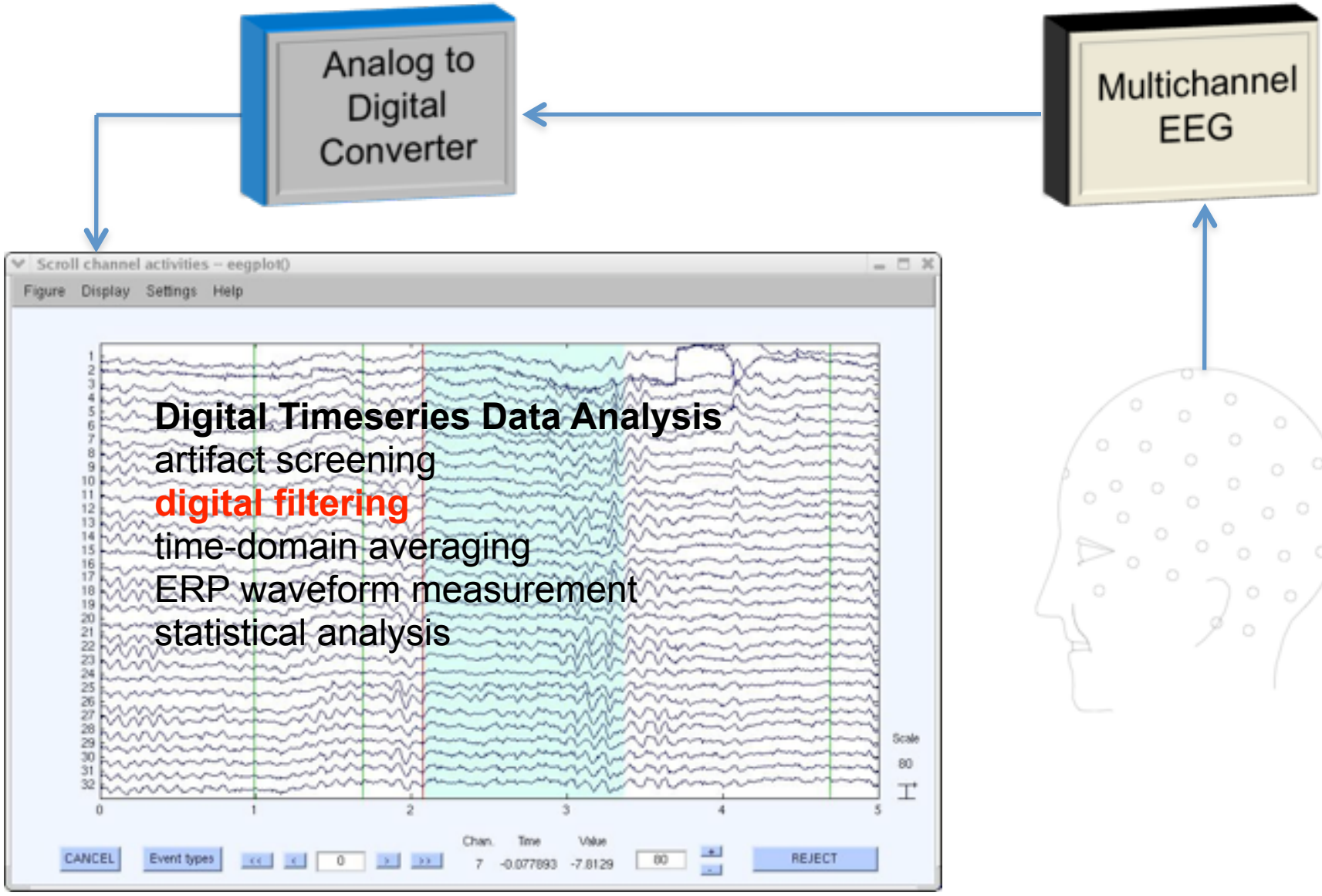


# Example 2: ICA decomposition, recomposition

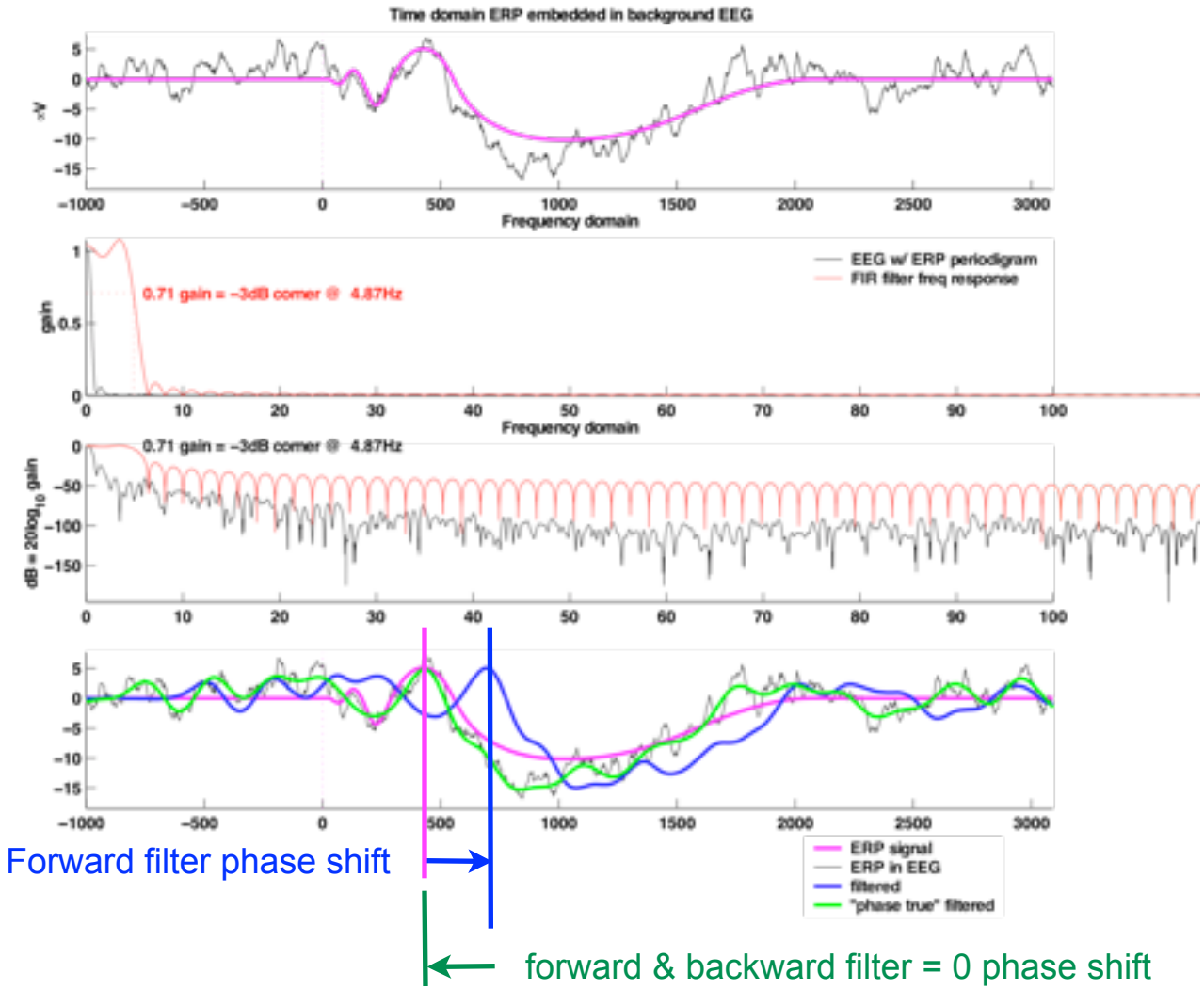


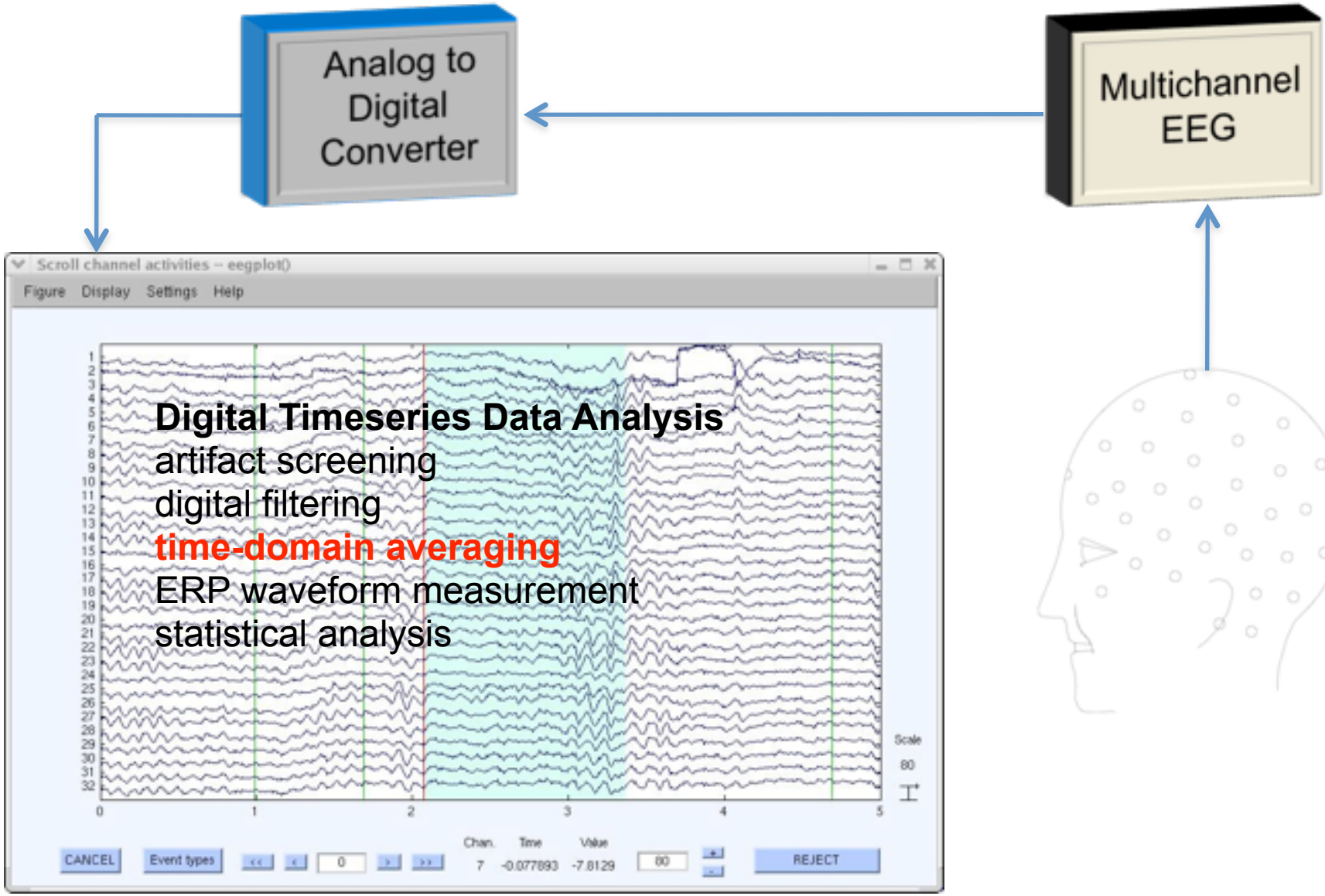
## Artifact strategy 3: Superior by far

# Record data without artifacts!

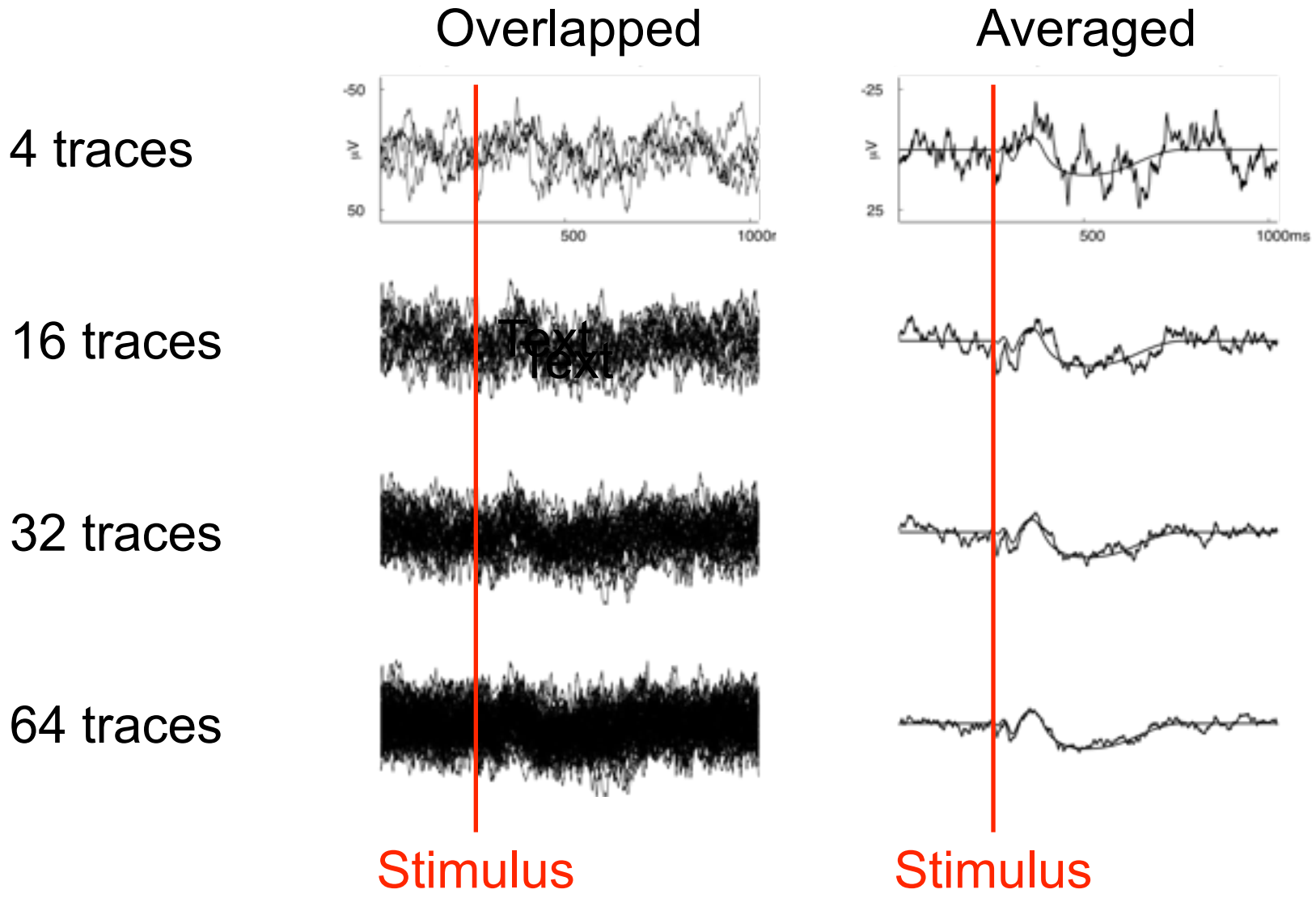

Analog to Digital Converter
Multichannel EEG
Scroll channel activities – eegplot()
Figure Display Settings Help
Digital Timeseries Data Analysis
artifact screening
digital filtering
time-domain averaging
ERP waveform measurement
statistical analysis
Scale
80
CANCEL
Event types
Chan. Time Value
7 -0.077893 -7.8129
REJECT

# Low pass filtering




Analog to Digital Converter
Multichannel EEG
Scroll channel activities – eegplot()
Figure Display Settings Help
Digital Timeseries Data Analysis
artifact screening
digital filtering
time-domain averaging
ERP waveform measurement
statistical analysis
Scale
80
CANCEL
Event types
Chan. Time Value
7 -0.077893 -7.8129
REJECT

# Finding ERP needles in the haystack



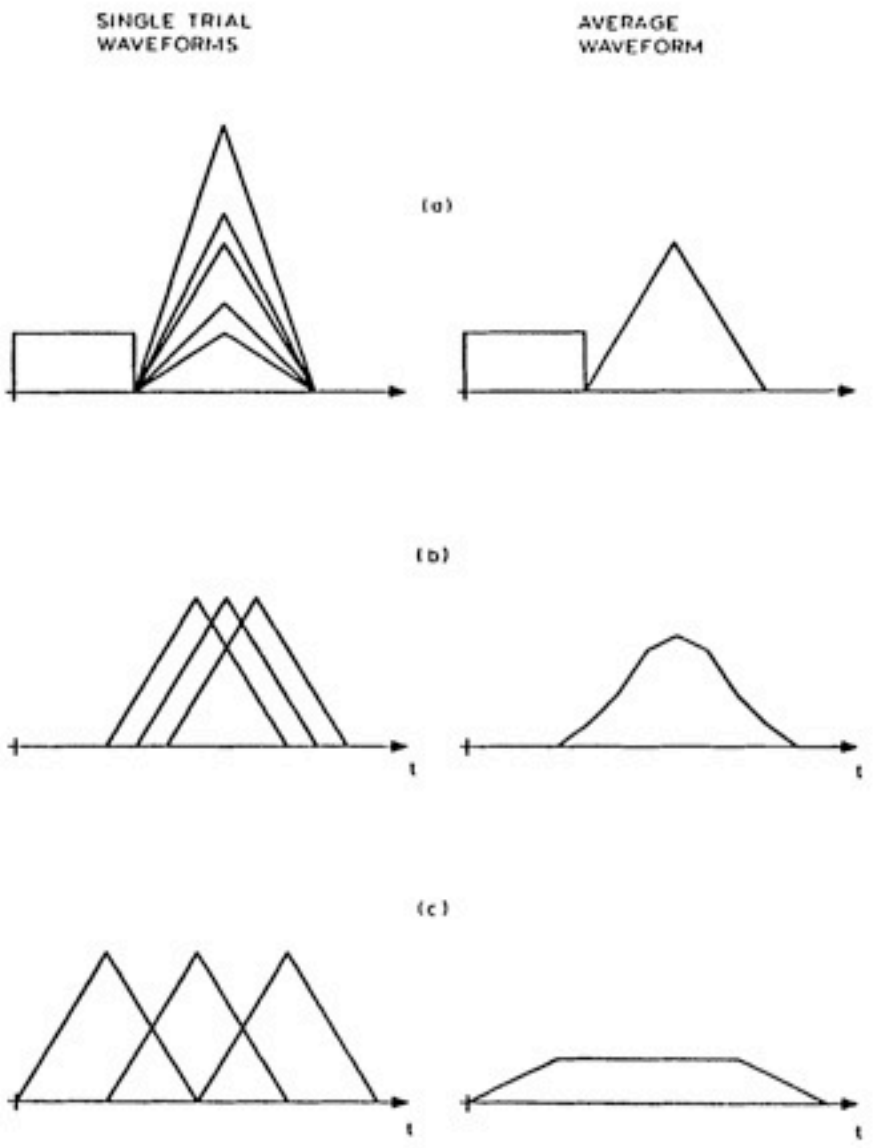
Need to average because EEG (50-100 uV) is larger than EP/ERP (1-20 uV)

ERPs can be isolated various signal averaging given certain assumptions.

Effect of averaging on noise is NOT a direct, linear function of the number of trials; the noise decreases as a function of the square root of the number of trials in the average. The signal to noise ratio increases as a function of the square root of the number of trials.

e.g., if signal = 20 uV, noise = 50 uV, signal to noise ratio 20:50 = .4
If # trials = 2, then signal to noise ratio increases by sqrt (2)
If # trials = 4, then signal to noise ratio increases by sqrt (4), etc.

# Violating "same ERP" assumption



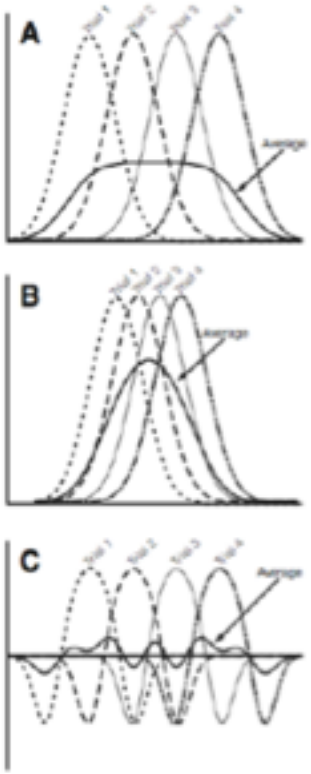

Variance in signal amplitude

Variance in signal latency

Variance in signal latency

Fig. 3. Hypothetical examples of the effects of amplitude modulation and latency variation upon single trial ERPs (left column) and average ERPs (right column). Row A illustrates the effect of amplitude modulation upon the late component of an ERP consisting of two components. Row B illustrates the effect of a relatively narrow range of latency variation (latency range equals 1/3 the duration of the wave). Row C illustrates the effect of a relatively wide range of latency variation (latency range equals the duration of the wave).

# Latency variability and averaging




**Violating "same ERP" assumption**

Signal is not monophasic

Figure 4.2 Example of the problem of latency variation. Each panel shows 4 single-trial waveforms, along with the average waveform. The same waveforms are present in panels A and B, but there is greater latency variability in panel A than in panel B, leading to a smaller peak amplitude and broader temporal extent for the average waveform in panel A. Panel C shows that when the single-trial waveforms are not monophasic, but instead have both positive and negative subcomponents, latency variability may lead to cancellation in the averaged waveform.

# Grand average ERP = average of subject average ERP

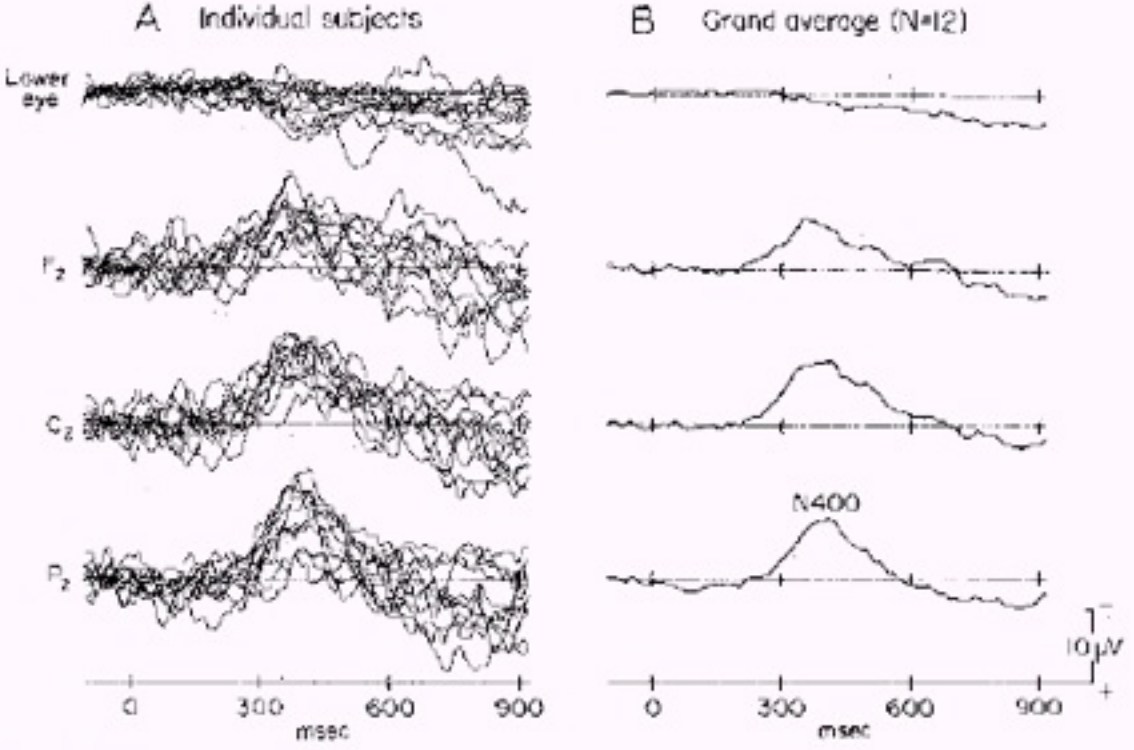
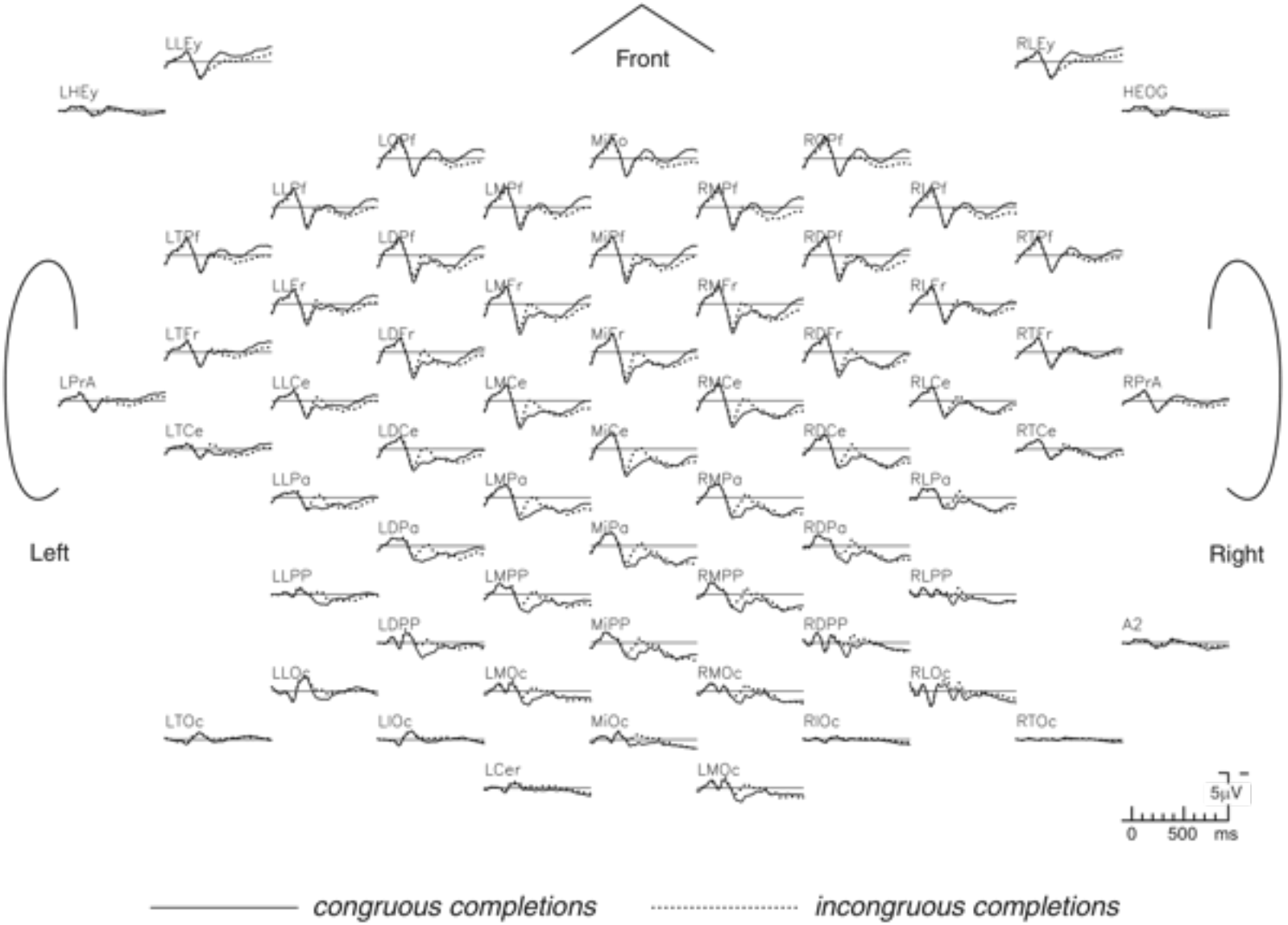


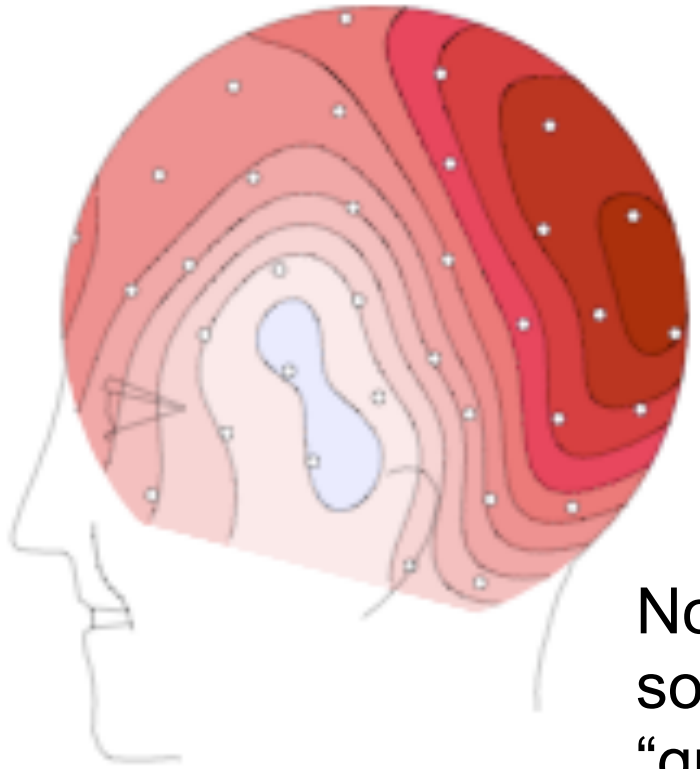

Fig. 2. Difference waves from experiment 2 (strong semantic incongruity). These difference waveforms were obtained by subtracting the averaged ERP's to the semantically congruous words from the ERP's to the semantically incongruous seventh words. Each superimposed tracing (A) represents the difference wave from one subject. The ERP's in (B) are the corresponding grand average waveforms over all 12 subjects.

# Grand average waveforms



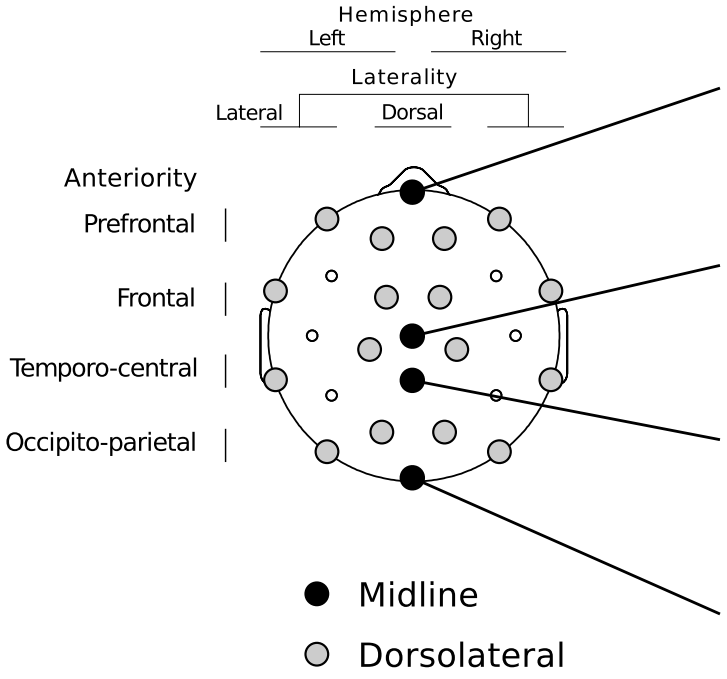
# Grand average distribution of scalp potentials

Note 1: values in between the electrodes are interpolated



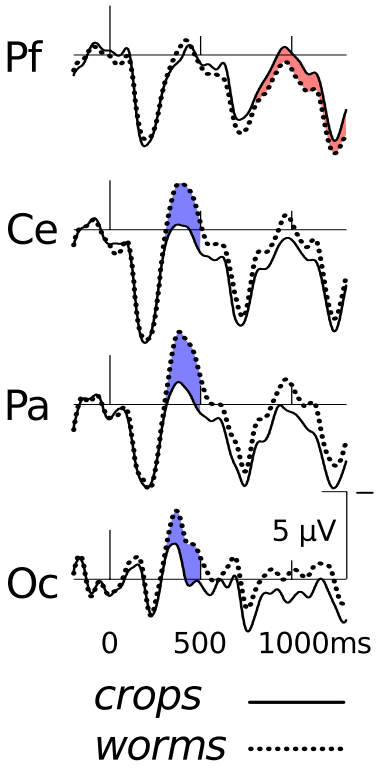
Note 2: *interpolated* sounds better than “guessed” but they mean the same

## A) Electrode locations



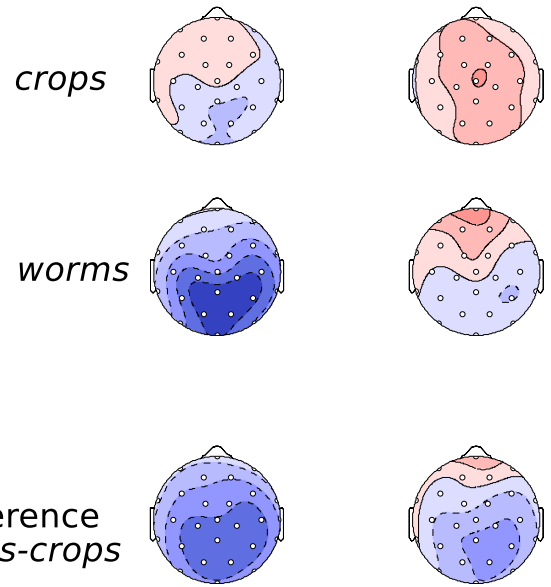

## B) Midline ERPs

Farmers grow



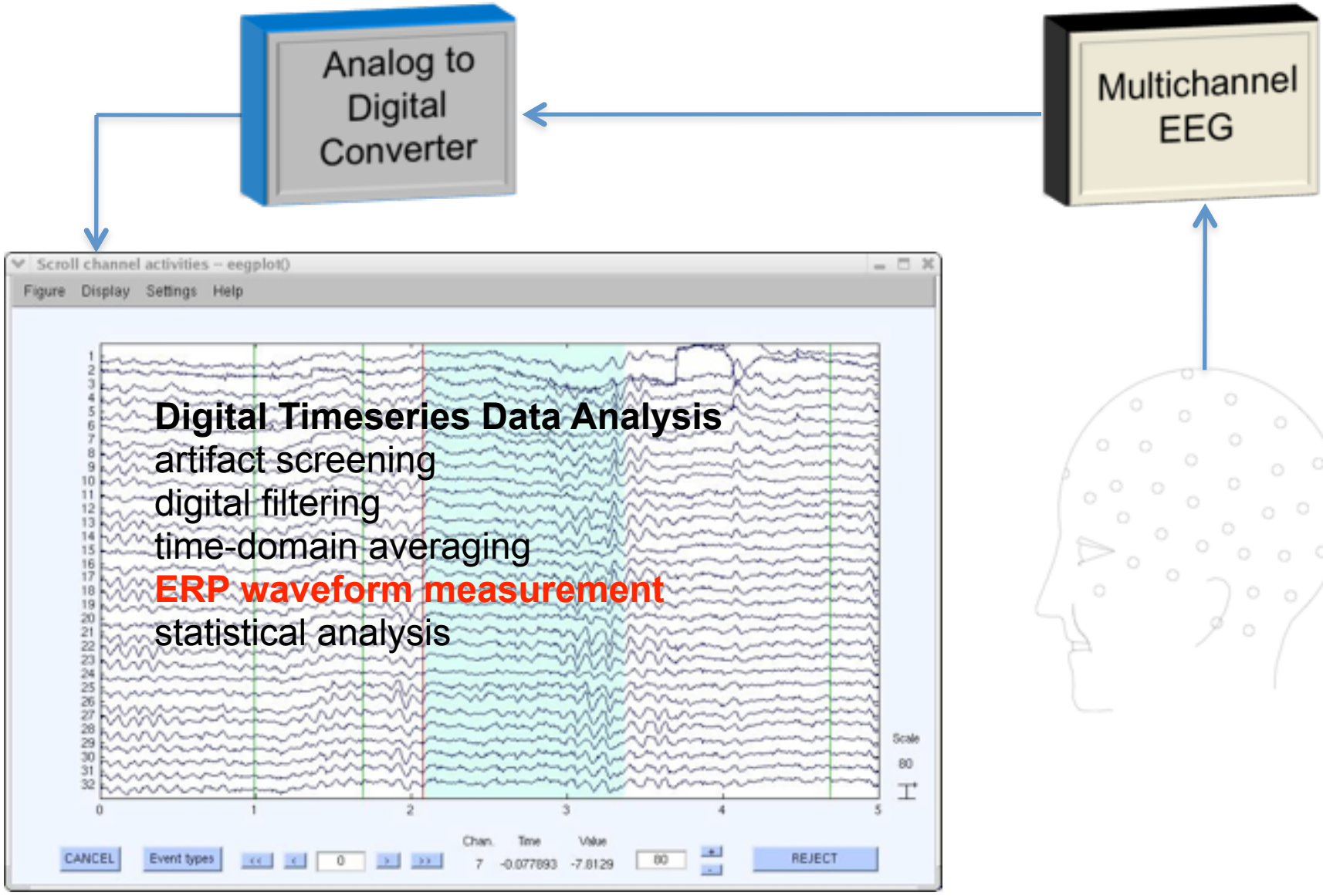

## C) N400 and Slow Wave

Farmers grow



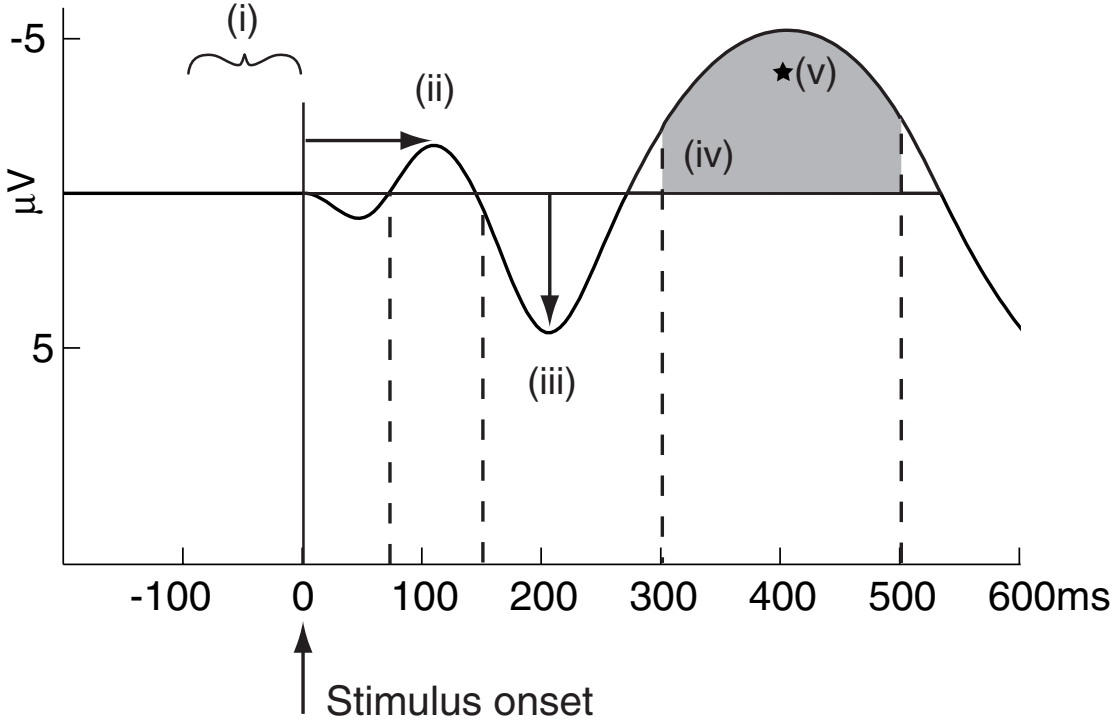

300-500ms 800-1300ms

N400 Slow Wave

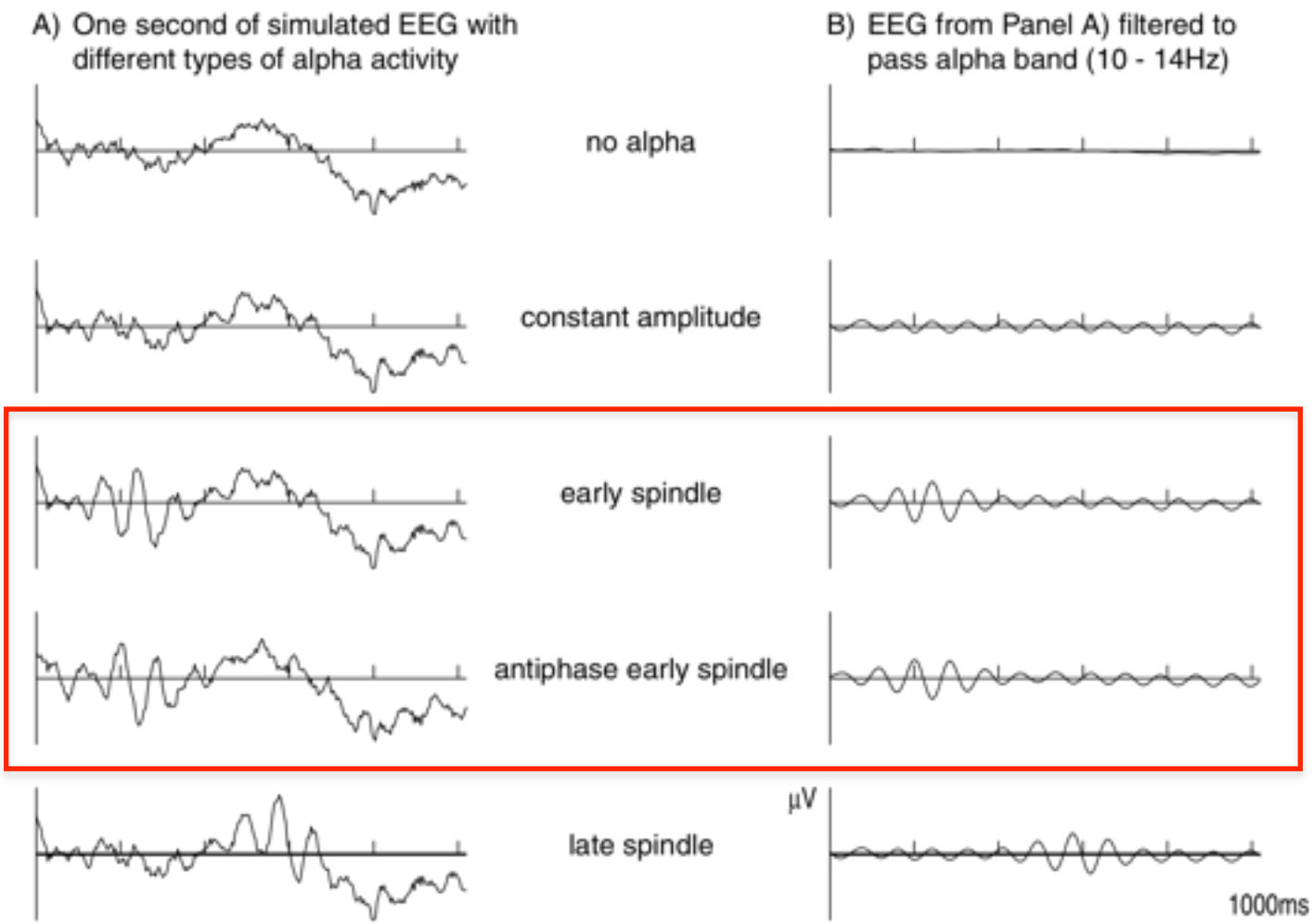

Analog to Digital Converter
Multichannel EEG
Scroll channel activities – eegplot()
Figure Display Settings Help
Digital Timeseries Data Analysis
artifact screening
digital filtering
time-domain averaging
ERP waveform measurement
statistical analysis
Scale
80
CANCEL
Event types
Chan. Time Value
7 -0.077893 -7.8129
REJECT

## Selected ERP data reduction measures

(i) 100ms prestimulus baseline
(ii) peak latency 75-150ms = 110ms
(iii) peak amplitude 150 - 300ms = 4.50μV
(iv) area 300 - 500ms = - 848 μVms
(v) mean amplitude 300 - 500ms = area/interval = -4.24μV

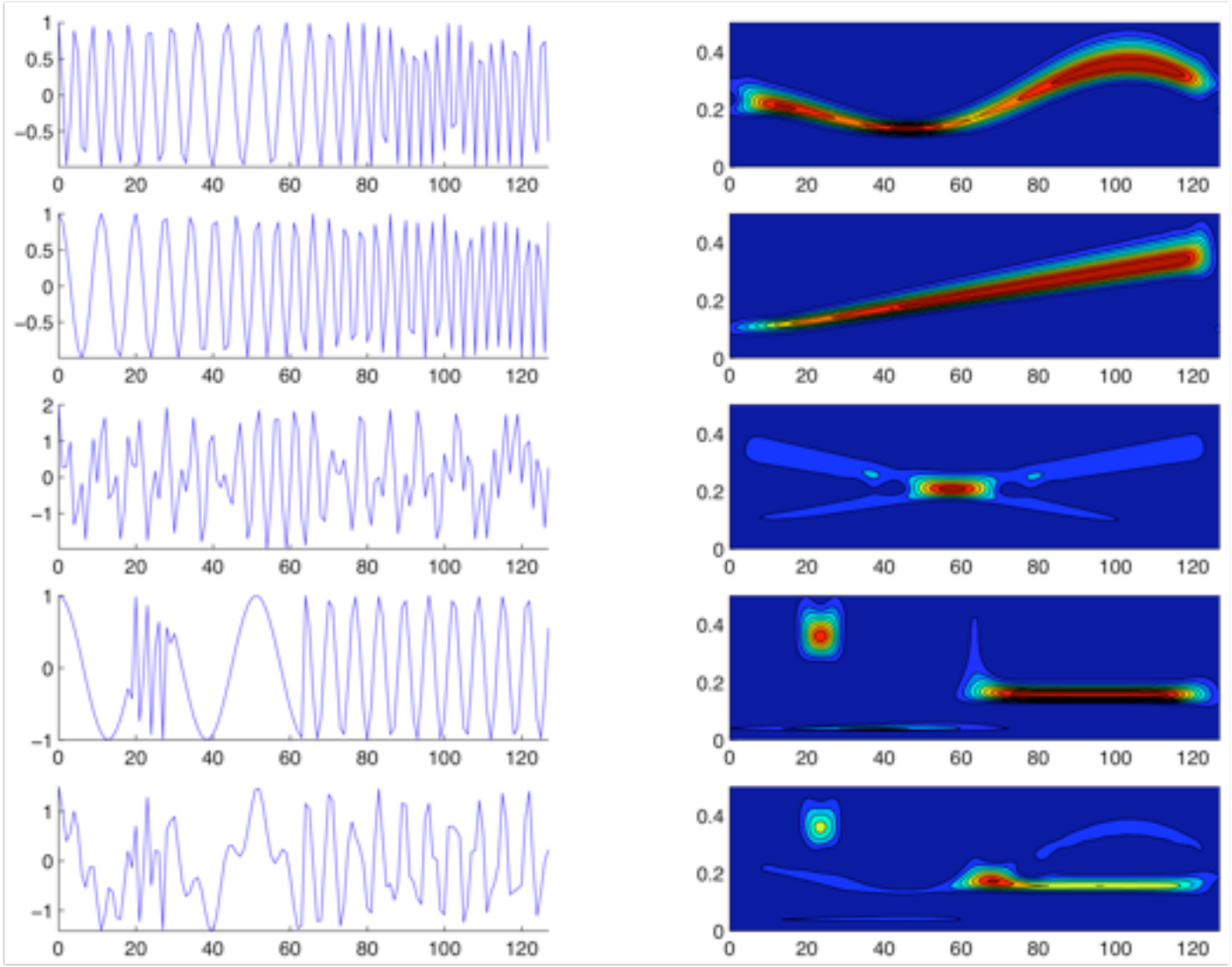


# Further information in the EEG?

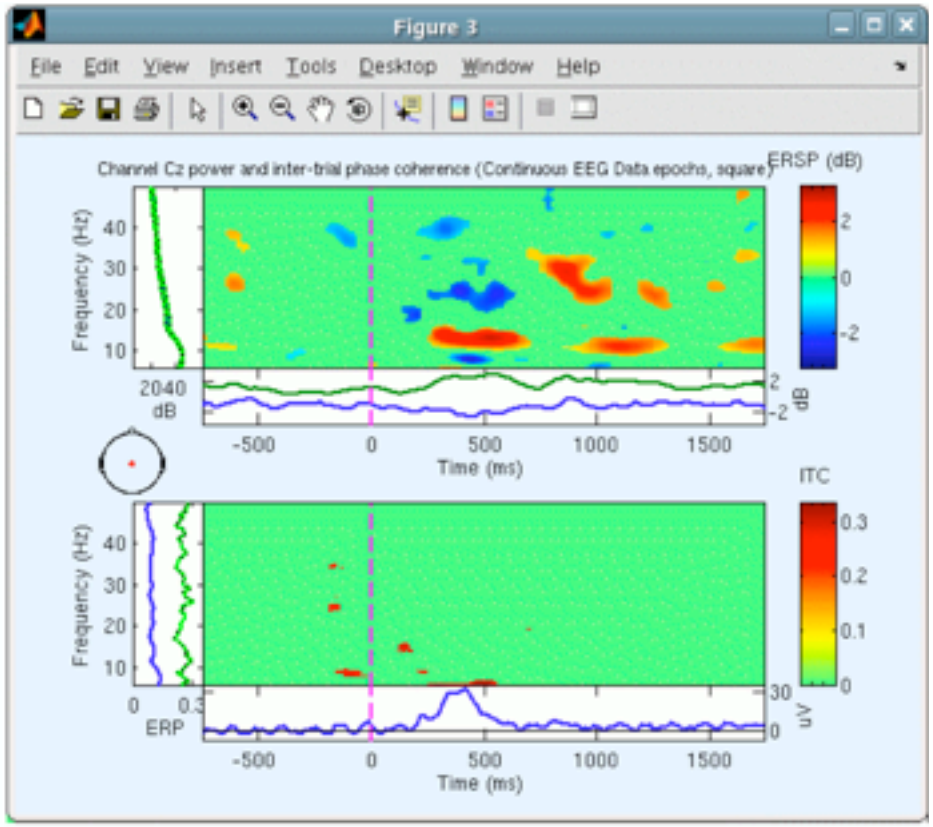



Average = 0

# Time x Frequency Analysis

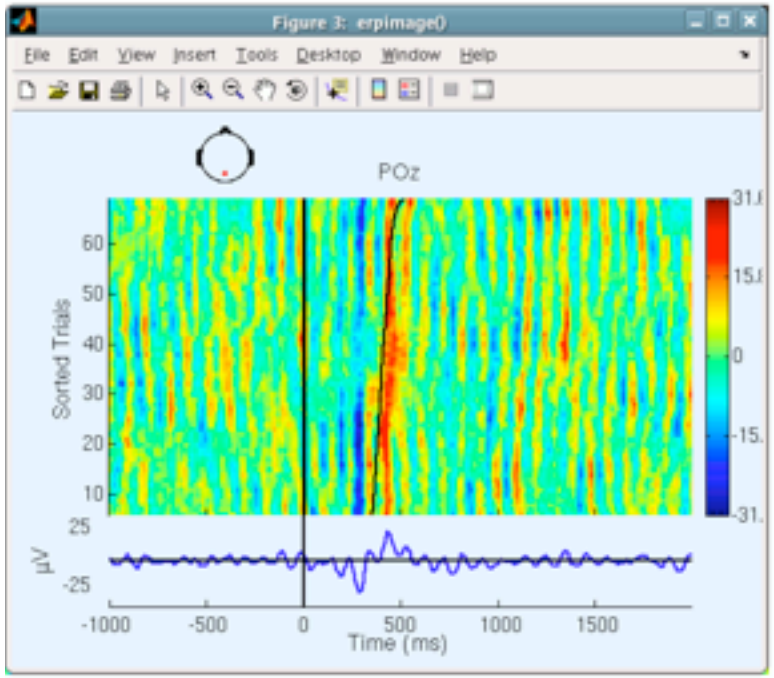


# Event-related time frequency analysis

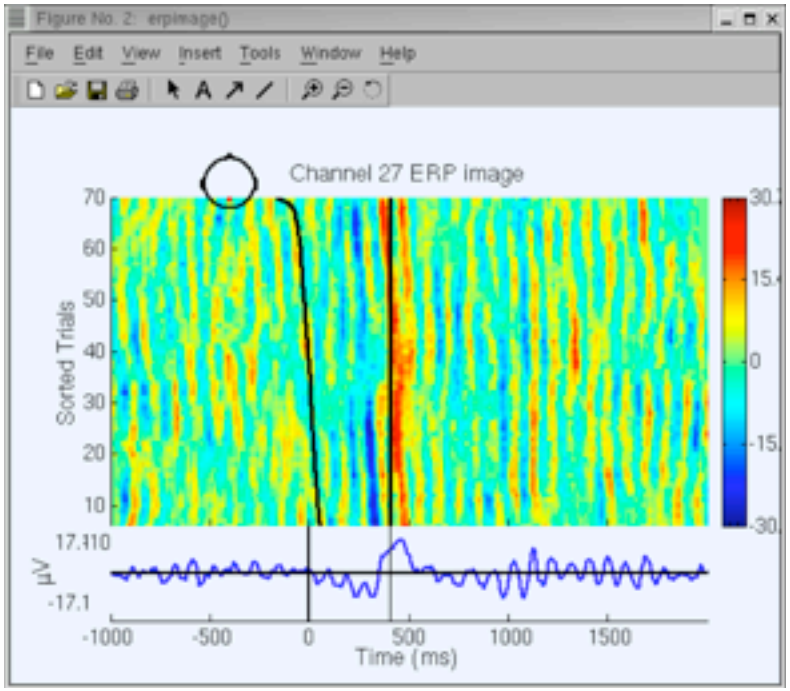


# Individual trials …

Time locked to stimulus




Time locked to response



## CSD – current source density

Examine current flowing out of the head at each point. This can be calculated by taking the second derivative of the distribution of voltage over the scalp (estimated from actual recordings).

CSD is insensitive to generators (dipoles) that are deep in the brain; it only picks up current flow from superficial sources.

Functions as “deblurring” high pass spatial filter