The Electroencephalogram

Basics in Recording EEG, Frequency Domain Analysis and its Applications

Announcements

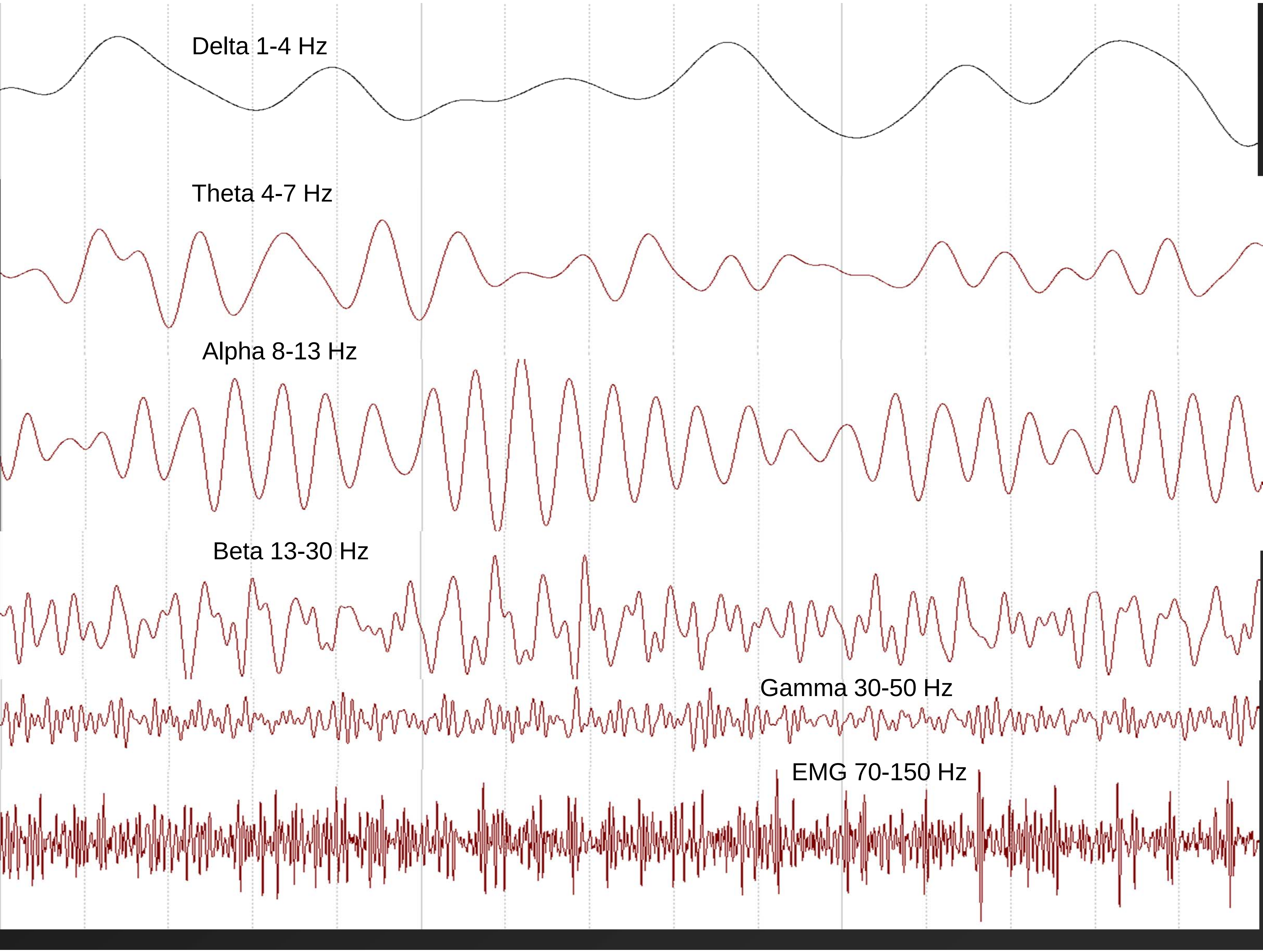
- Papers: 1 or 2 paragraph prospectus due no later than Monday March 28
- SB 1467
- 3x5s

The Electroencephalogram

Basics in Recording EEG, Frequency Domain Analysis and its Applications

Electroencephalogram (EEG)

- The EEG--an oscillating voltage recorded on scalp surface
  - Reflects Large # Neurons
  - Is small voltage
- Bands of activity and behavioral correlates
  - Gamma 30-50 Hz
  - Beta 13-30 Hz
  - Alpha 8-13 Hz
  - Theta 4-8 Hz
  - Delta 0.5-4 Hz


Delta 1-4 Hz
Theta 4-7 Hz
Alpha 8-13 Hz
Beta 13-30 Hz
Gamma 30-50 Hz
EMG 70-150 Hz

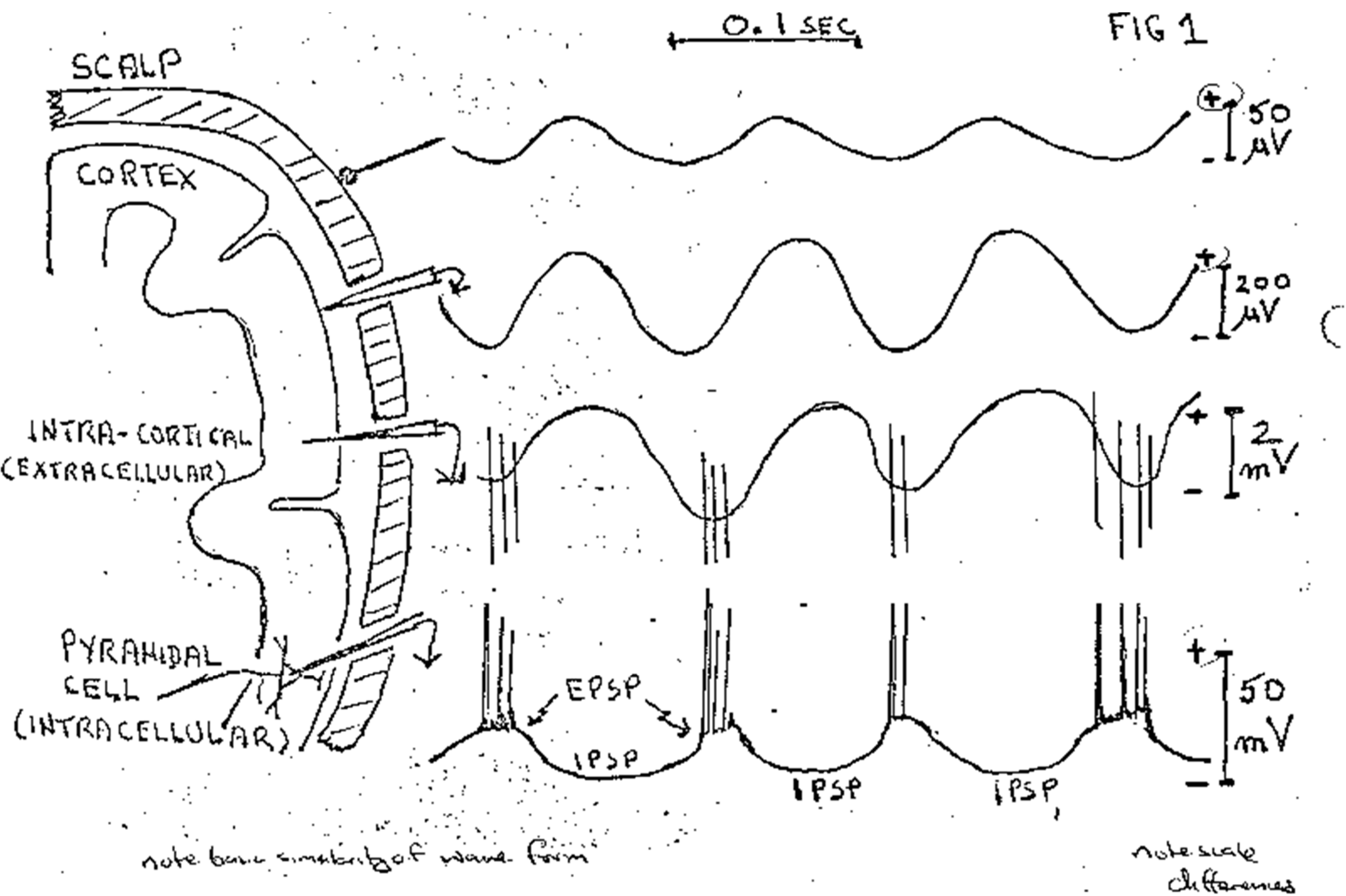
Utility of EEG

- *Relatively* noninvasive
- Excellent time resolution

Sources of scalp potentials

- Glial Cells – minimal, some DC steady potentials
- Neurons
  - Action Potentials – NO, brain tissue has strong capacitance effects, acting as Low Pass filter
  - Slow waves
    - Synaptic potentials – YES, both IPSPs and EPSPs from functional synaptic units are major contributors
    - Afterpotentials – May contribute to a lesser extent

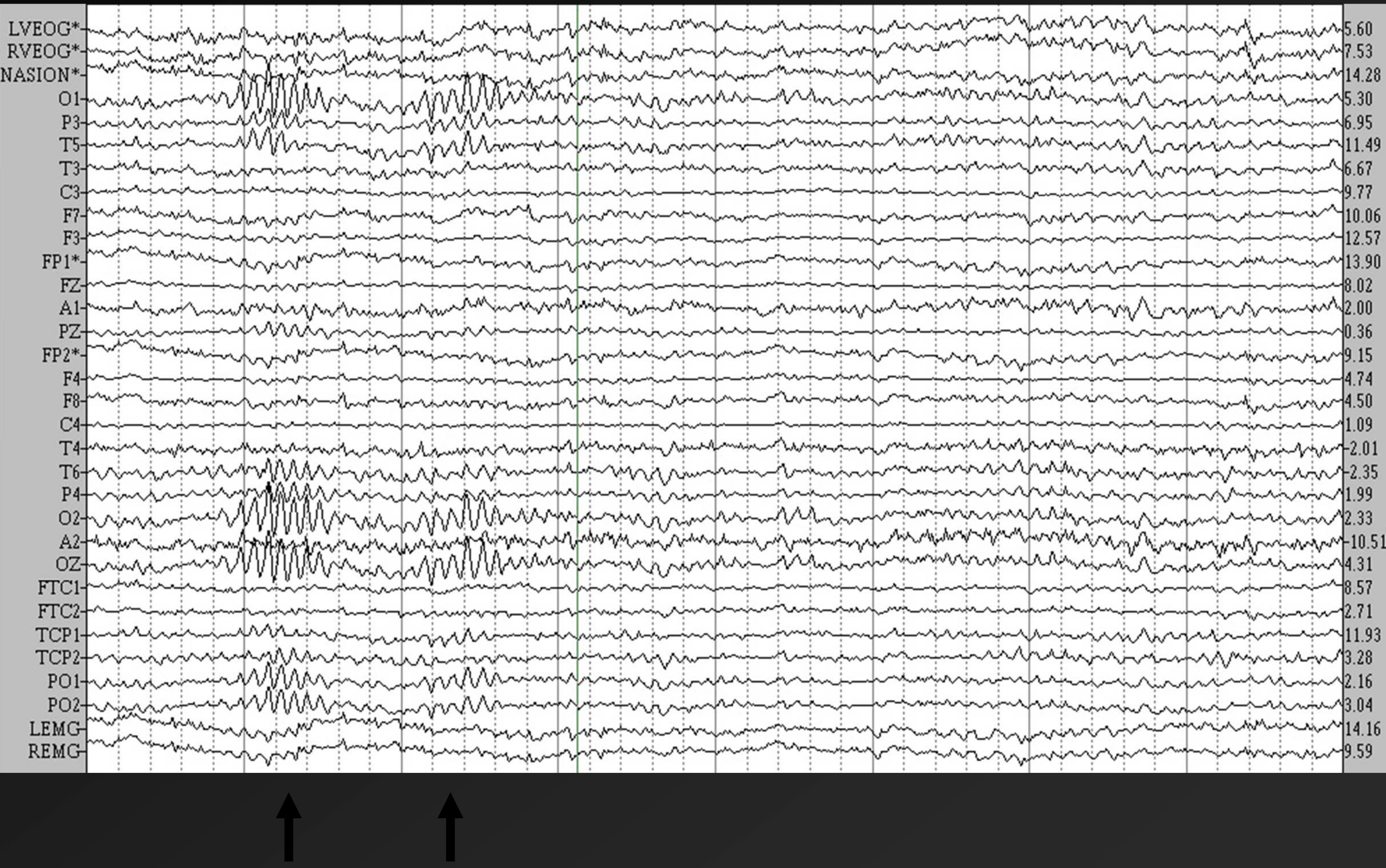
FIG 1


0.1 SEC
SCALP
CORTEX
50 µV
200 µV
INTRA-CORTICAL (EXTRACELLULAR)
2 mV
PYRAMIDAL CELL (INTRACELLULAR)
EPSP
IPSP
IPSP
IPSP
50 mV
+
-
note basic similarity of wave form
note scale differences

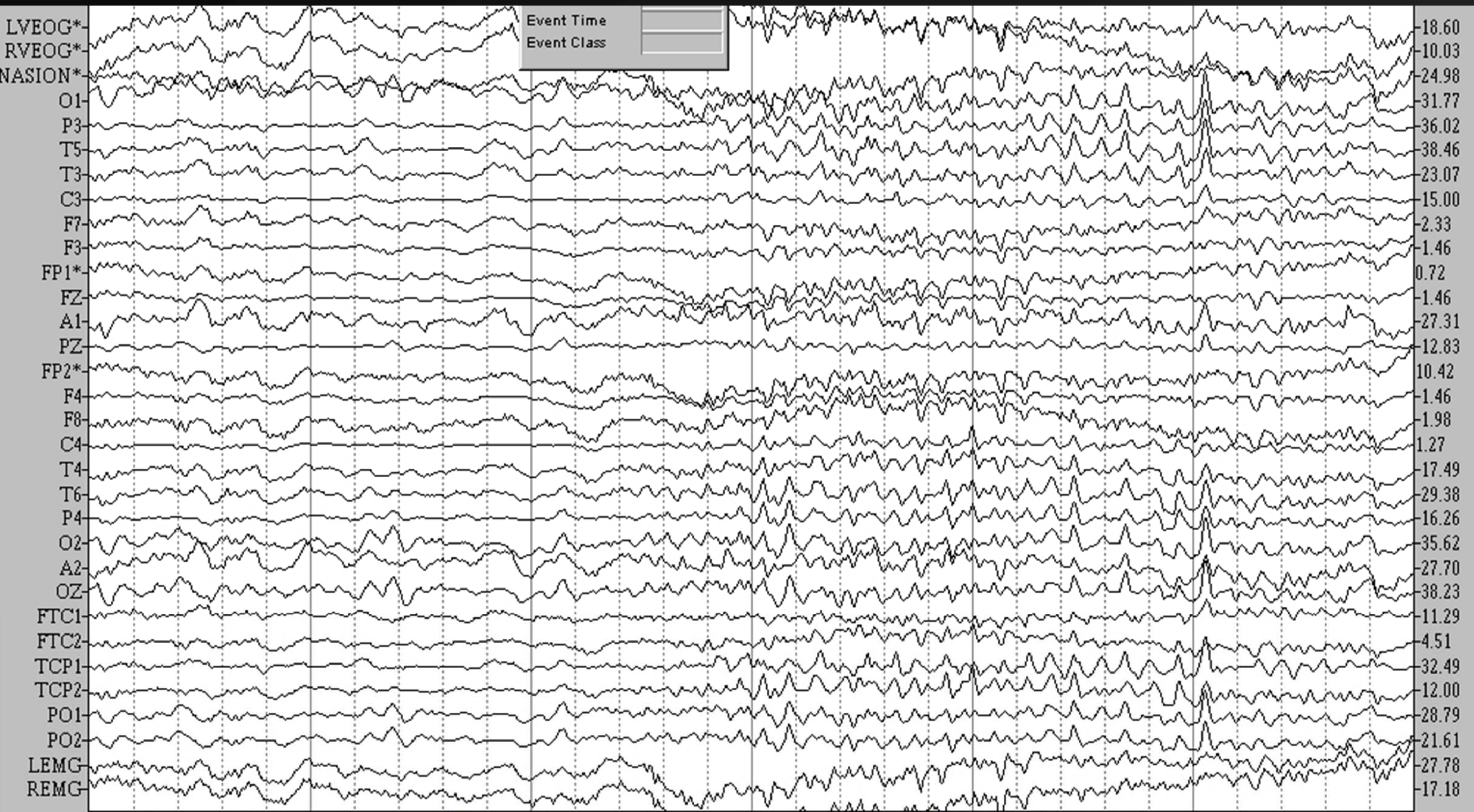
Alpha and Synchronization

- Why Alpha?
  - It is obvious and hard to miss!
  - Accounts for ~70% of EEG activity in adult human brain
- From where, Alpha?
  - Historically, thought to be thalamocortial looping
  - Adrian (1935) demolished that theory
    - Recorded EEG simultaneously in cortex and thalamus
    - Damage to cortex did not disrupt thalamic alpha rhythmicity
    - Damage to thalamus DID disrupt cortical alpha rhythmicity
  - Thalamic rhythmicity remains even in decorticate preparations (Adrian, 1941)
  - Removal of ½ thalamus results in ipsilateral loss of cortical alpha

Next

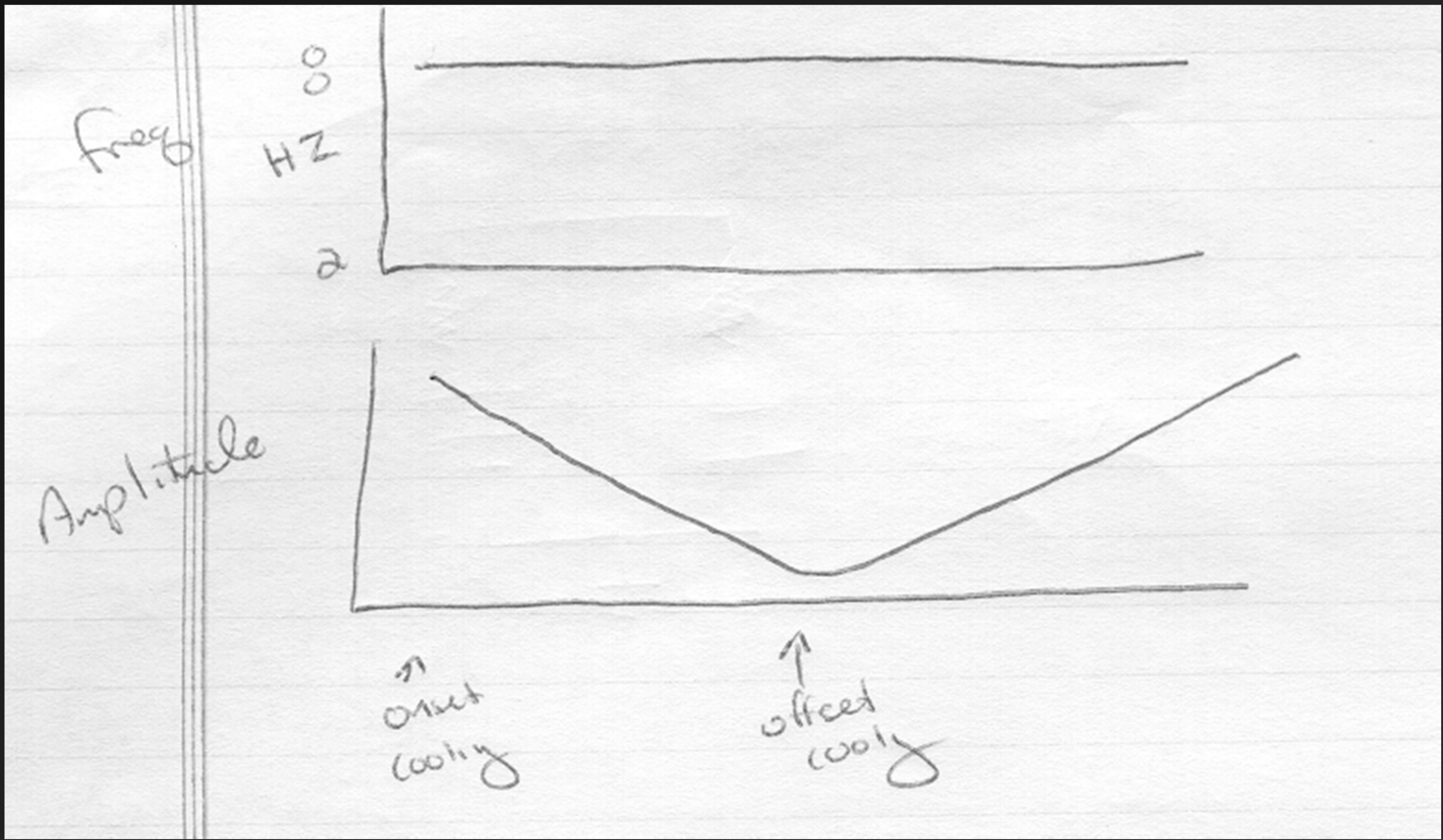


LVEOG* 5.60
RVEOG* 7.53
NASION* 14.28
O1 5.30
P3 6.95
T5 11.49
T3 6.67
C3 9.77
F7 10.06
F3 12.57
FP1* 13.90
FZ 8.02
A1 2.00
PZ 0.36
FP2* 9.15
F4 4.74
F8 4.50
C4 1.09
T4 -2.01
T6 -2.35
P4 1.99
O2 2.33
A2 -10.51
OZ 4.31
FTC1 8.57
FTC2 2.71
TCP1 11.93
TCP2 3.28
PO1 2.16
PO2 3.04
LEMG 14.16
REMG 9.59


Event Time
Event Class
LVEOG*
RVEOG*
NASION*
O1
P3
T5
T3
C3
F7
F3
FP1*
FZ
A1
PZ
FP2*
F4
F8
C4
T4
T6
P4
O2
A2
OZ
FTC1
FTC2
TCP1
TCP2
PO1
PO2
LEMG
REMG
18.60
10.03
24.98
31.77
36.02
38.46
23.07
15.00
2.33
1.46
0.72
1.46
27.31
12.83
10.42
1.46
1.98
1.27
17.49
29.38
16.26
35.62
27.70
38.23
11.29
4.51
32.49
12.00
28.79
21.61
27.78
17.18

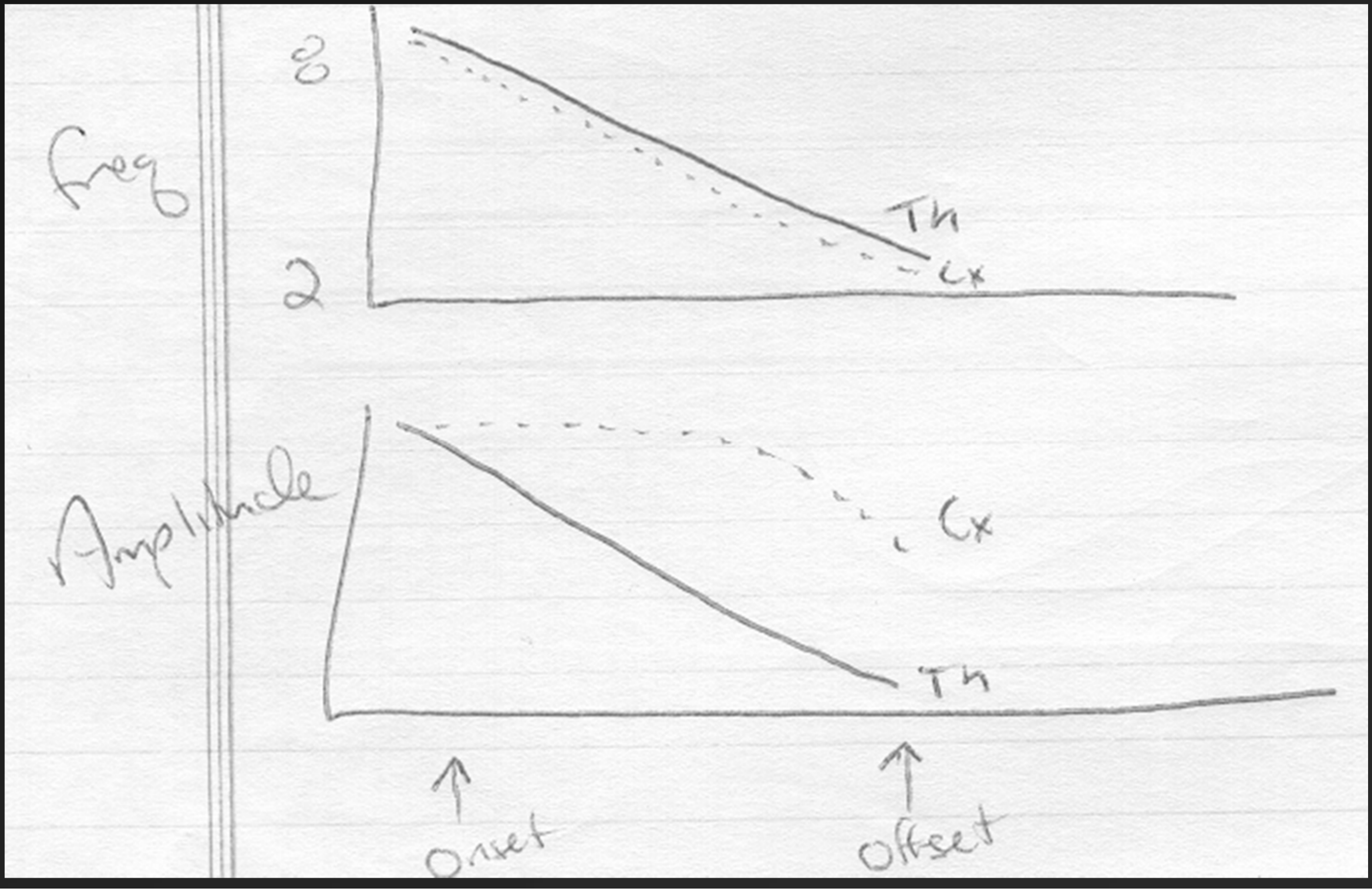
Alpha and Synchronization

- Andersen and Andersen (1968)
  - Cooling of Cortex resulted in change in amplitude but not frequency of Alpha



Alpha and Synchronization

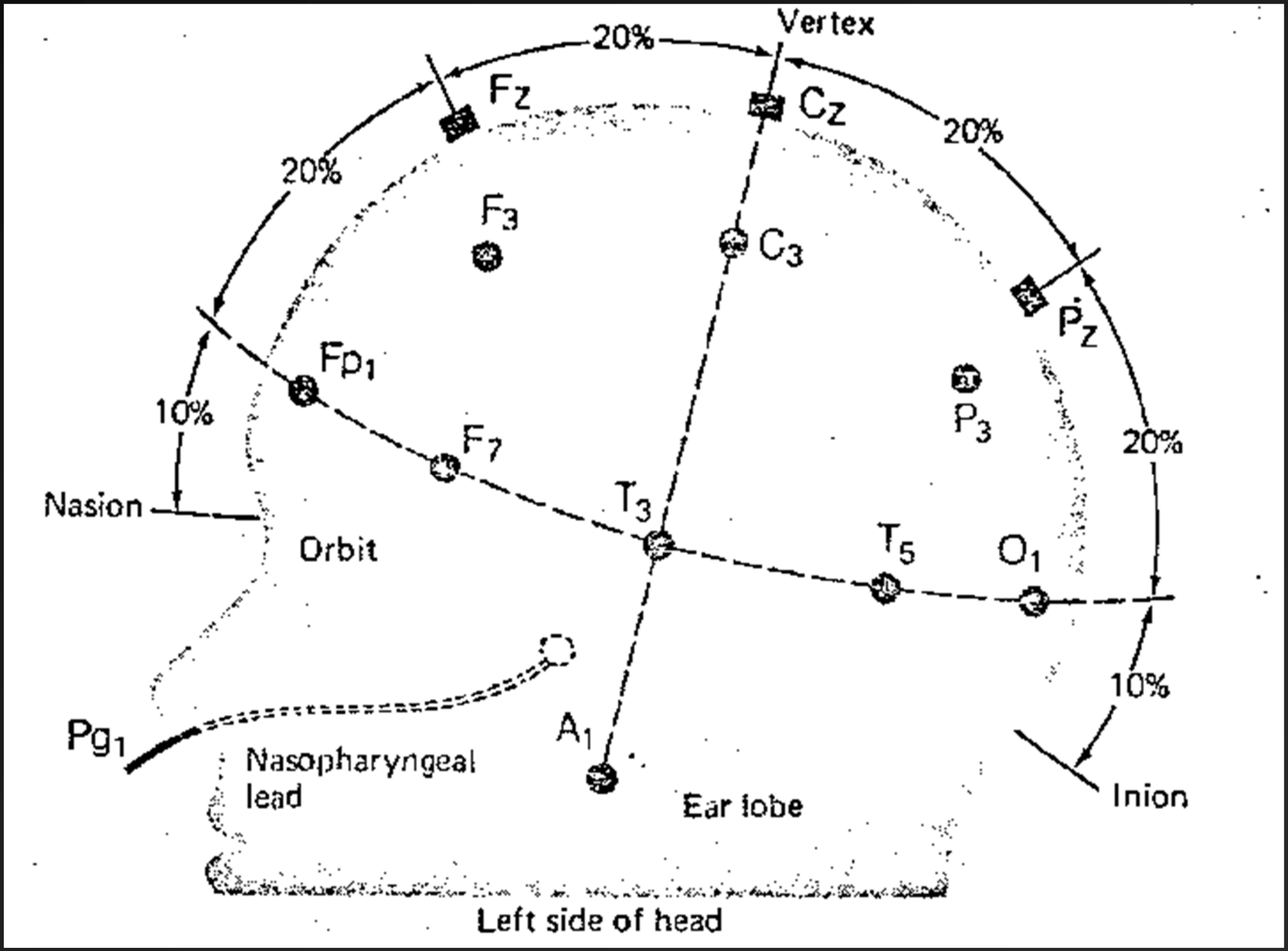
- Andersen and Andersen (1968)
  - Cooling of Thalamus resulted in change in amplitude and frequency of Alpha at both thalamus and cortex



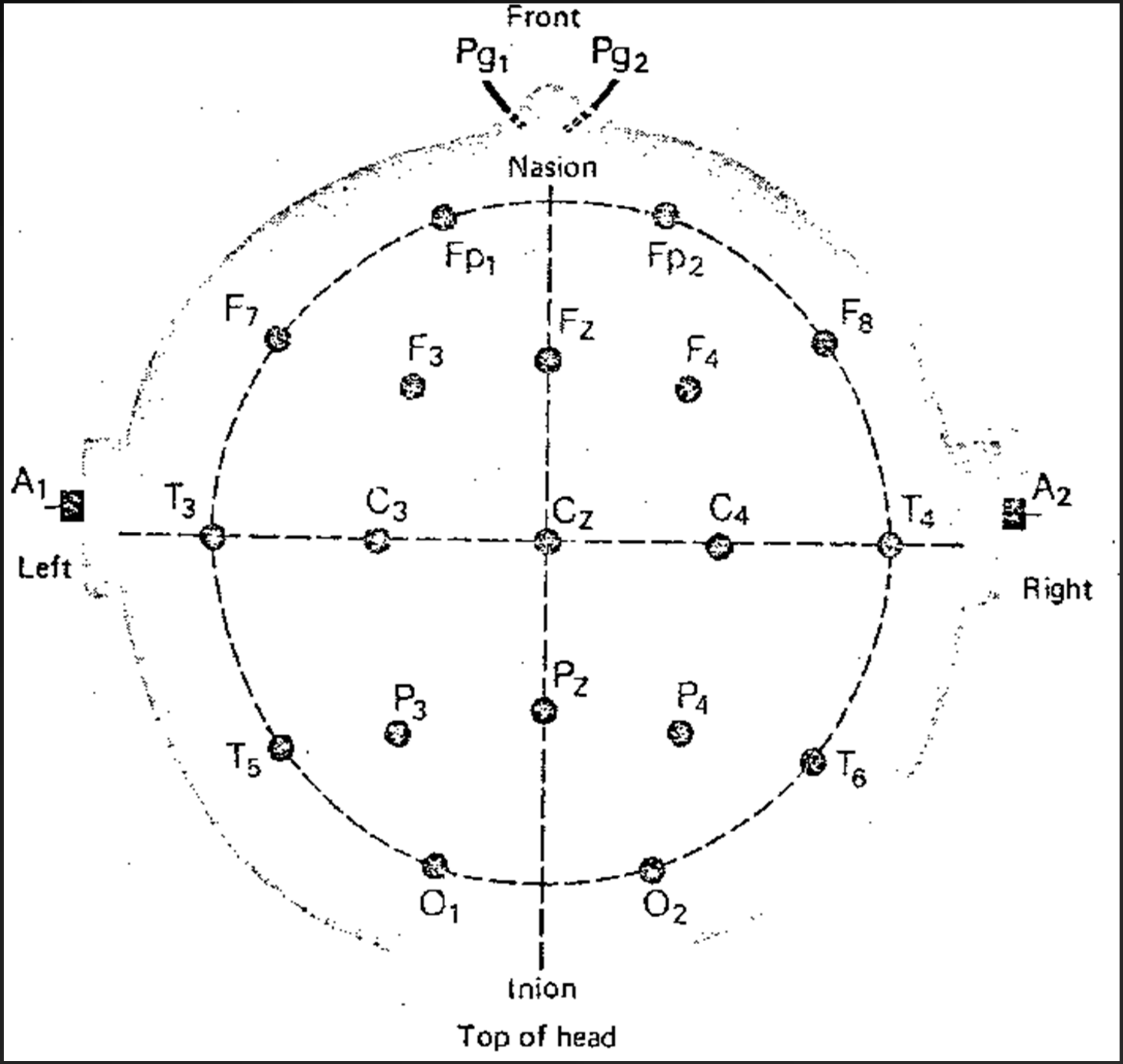
Alpha and Synchronization

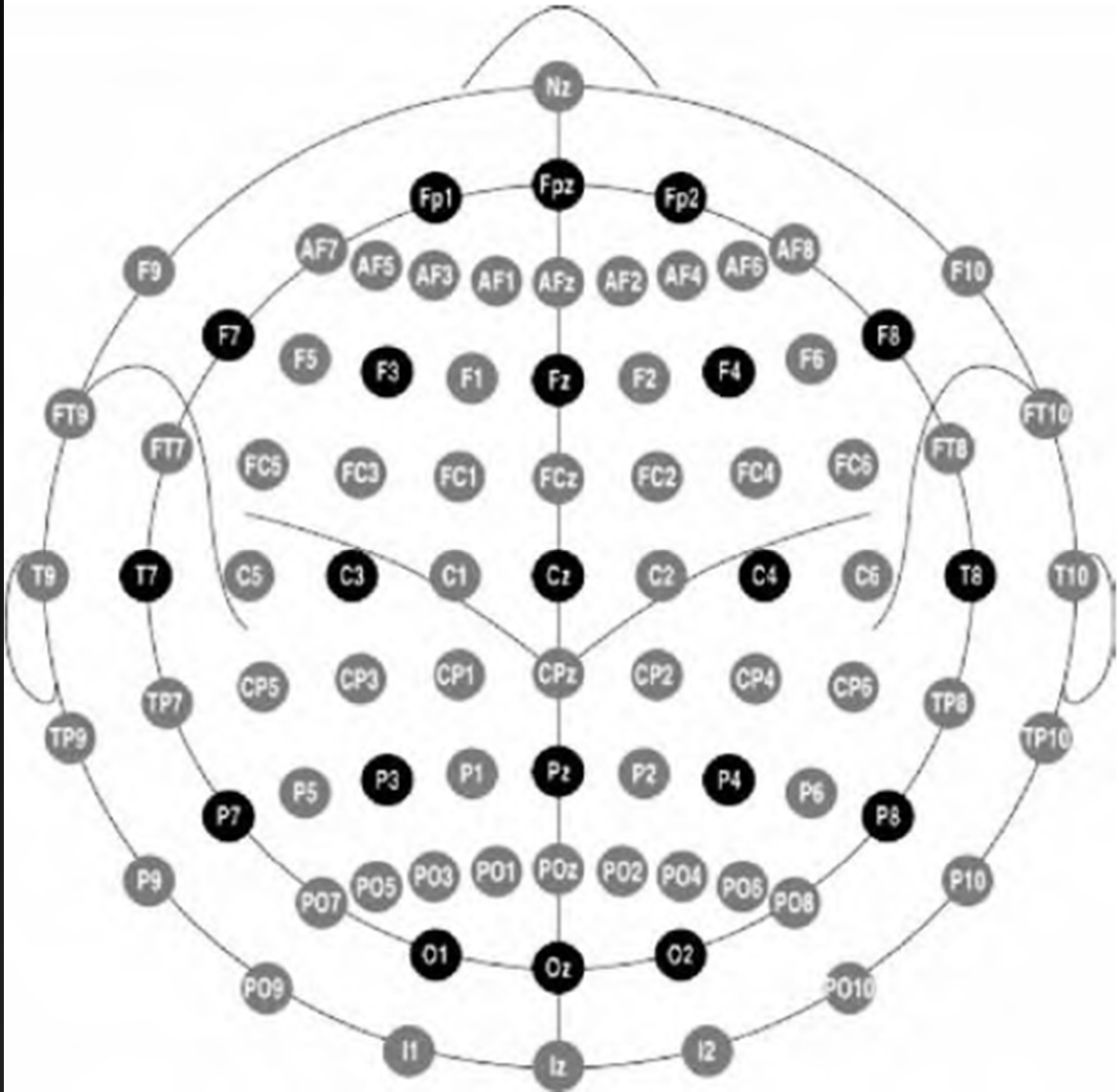
- In sum, Thalamus drives the alpha rhythmicity of the EEG
  - Cortex certainly does feedback to thalamus, but thalamus is responsible for driving the EEG
  - Particularly the Reticularis nucleus (Steriade et al. 1985)
- What causes change from rhythmicity to desynchronization?
  - Afferent input to thalamic relay nuclei
  - Mode-specific enhancement observed

Recording EEG



Recording EEG





Nz
Fp1
Fpz
Fp2
AF7
AF5
AF3
AF1
AFz
AF2
AF4
AF6
AF8
F9
F7
F5
F3
F1
Fz
F2
F4
F6
F8
F10
FT9
FT7
FC5
FC3
FC1
FCz
FC2
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P9
P7
P5
P3
P1
Pz
P2
P4
P6
P8
P10
PO9
PO7
PO5
PO3
PO1
POz
PO2
PO4
PO6
PO8
PO10
O1
Oz
O2
I1
Iz
I2

Electrodes, Electrolyte, Preparation

- Ag-AgCl preferred, Gold OK if slowest frequencies not of interest
  - Polarizing electrodes act as capacitors in series with signal
- Electrolyte: ionic, conductive
- Affixing
  - Subcutaneous needle electrodes (OUCH)
  - Collodion (YUCK)
  - EC-2 paste; lesser of the evils
  - Electrocap

Recording References

- Measure voltage potential differences
  - Difference between what and what else?
- "Monopolar" versus Bipolar
  - No truly inactive site, so monopolar is a relative term
  - Relatively monopolar options
    - Body – BAD IDEA
    - Head
      - Linked Ears or Mastoids
      - Tip of Nose
- Reference choice nontrivial (more later) as it will change your ability to observe certain signals

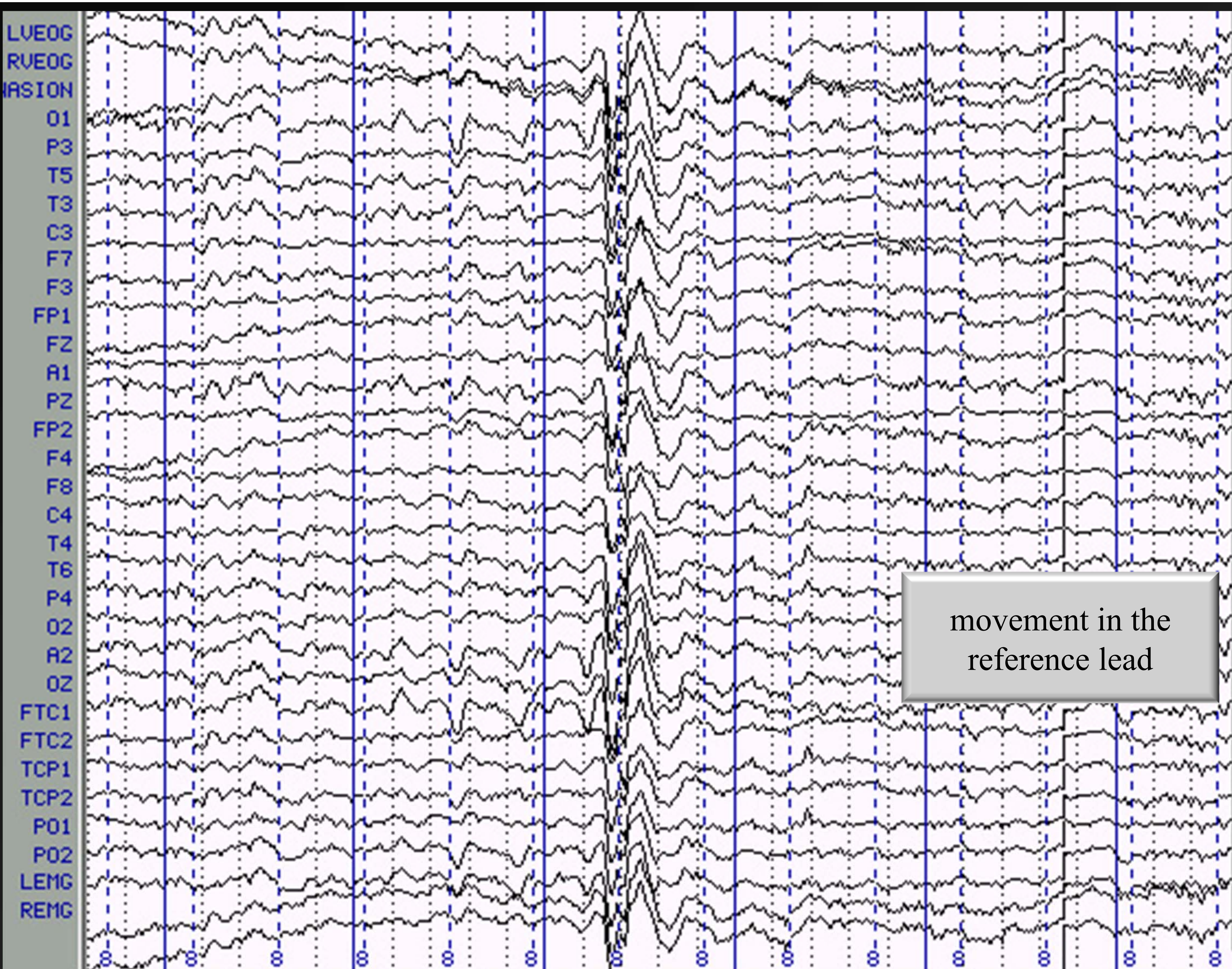
Recording References

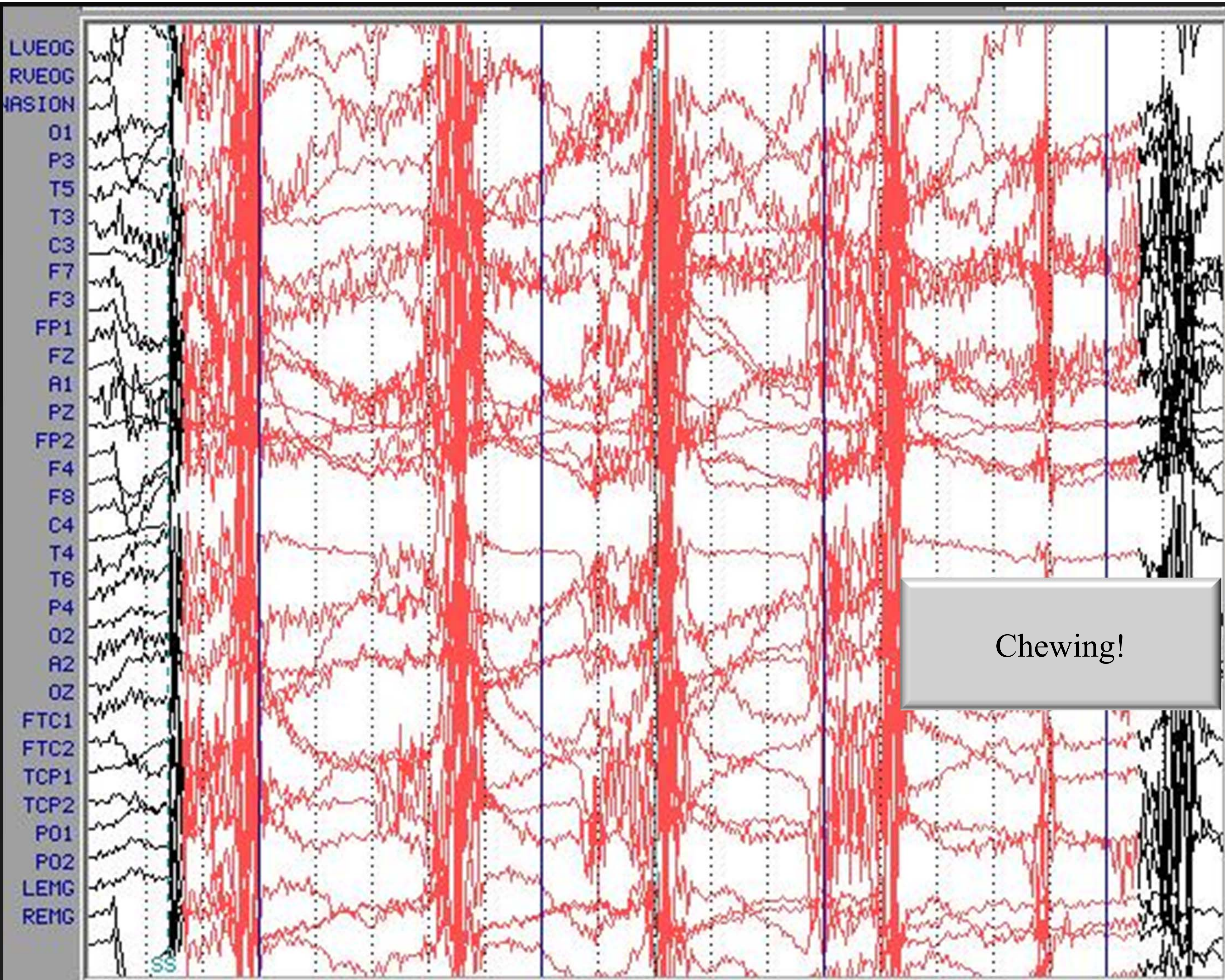
- Bipolar recording
  - Multiple active sites
    - Sensitive to differences between electrodes
    - With proper array, sensitive to local fluctuations (e.g. spike localization)
- Off-line derivations
  - Averaged Mastoids
  - Average Reference (of EEG Leads)
    - With sufficient # electrodes and surface coverage, approximates inactive site (signals cancel out)
    - Artifacts "average in"
  - Current Source Density (more in advance topics)

Dreaded Artifacts

- Three sources
  - 60-cycle noise
    - Ground subject
    - 60 Hz Notch filter
  - Muscle artifact
    - No gum!
    - Use headrest
    - Measure EMG and reject/correct for influence
  - Eye Movements
    - Eyes are dipoles
    - Reject ocular deflections including blinks
    - Use correction procedure (more in advance lecture)

Name That Artifact!


LVEOG
RVEOG
ASION
O1
P3
T5
T3
C3
F7
F3
FP1
FZ
A1
PZ
FP2
F4
F8
C4
T4
T6
P4
O2
A2
OZ
FTC1
FTC2
TCP1
TCP2
PO1
PO2
LEMG
REMG
movement in the
reference lead


LVEOG
RVEOG
NASION
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P3
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C3
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FP1
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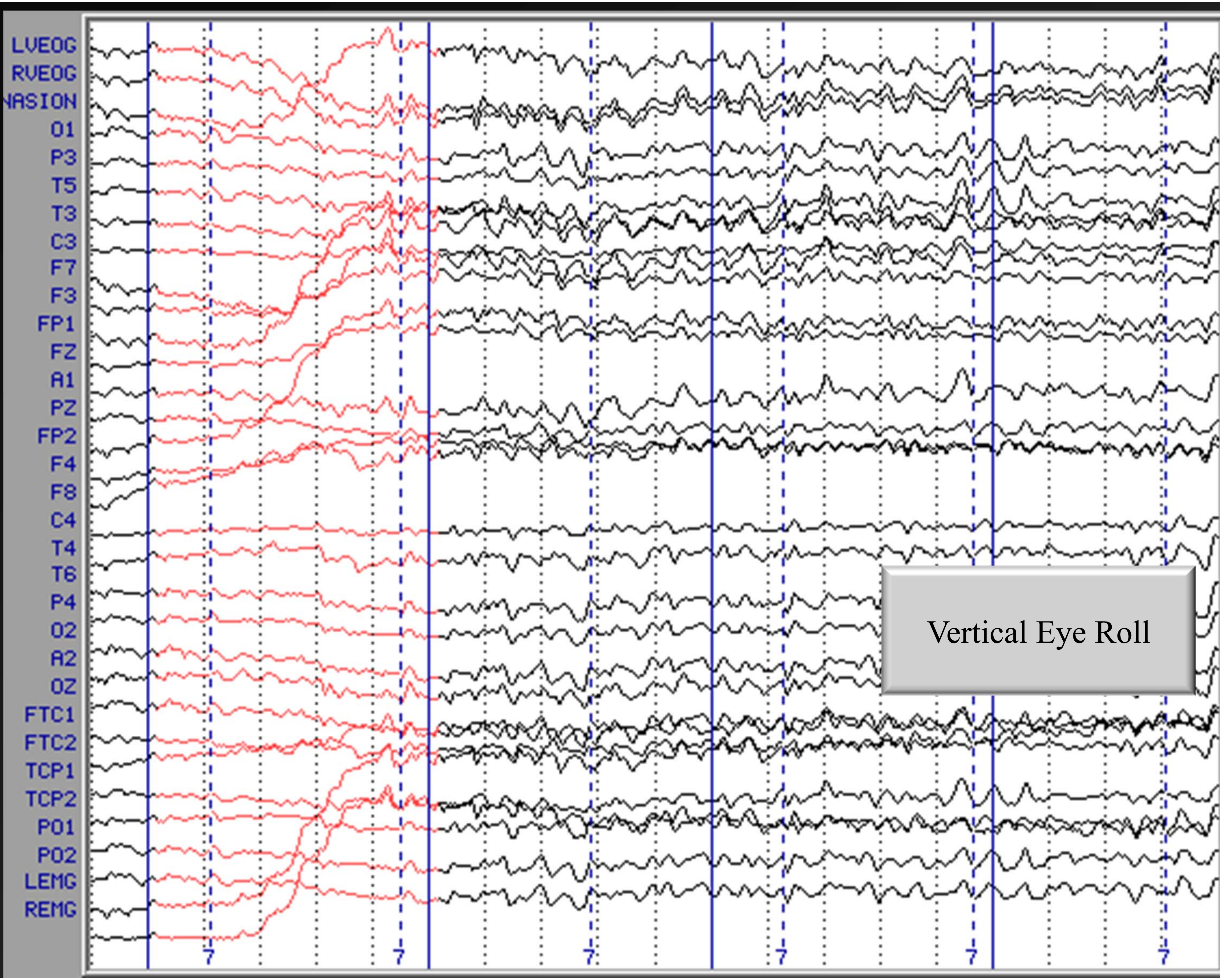
PZ
FP2
F4
F8
C4
T4
T6
P4
O2
A2
OZ
FTC1
FTC2
TCP1
TCP2
PO1
PO2
LEMG
REMG
SS
Chewing!


LVEOG
RVEOG
NASION
O1
P3
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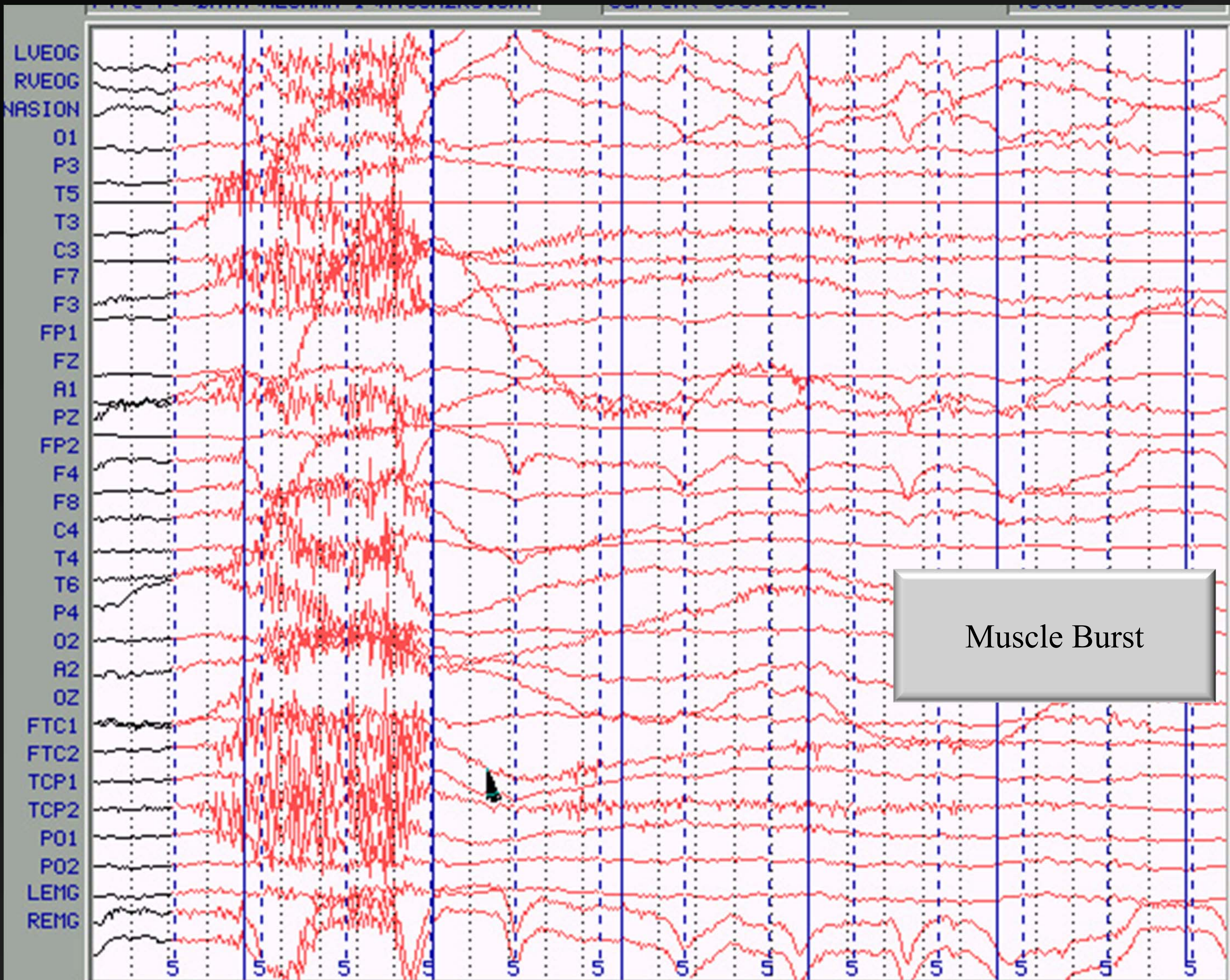
T3
C3
F7
F3
FP1
FZ
A1
PZ
FP2
F4
F8
C4
T4
T6
P4
O2
A2
OZ
FTC1
FTC2
TCP1
TCP2
PO1
PO2
LEMG
REMG
Vertical Eye Roll


LVEOG
RVEOG
NASION
O1
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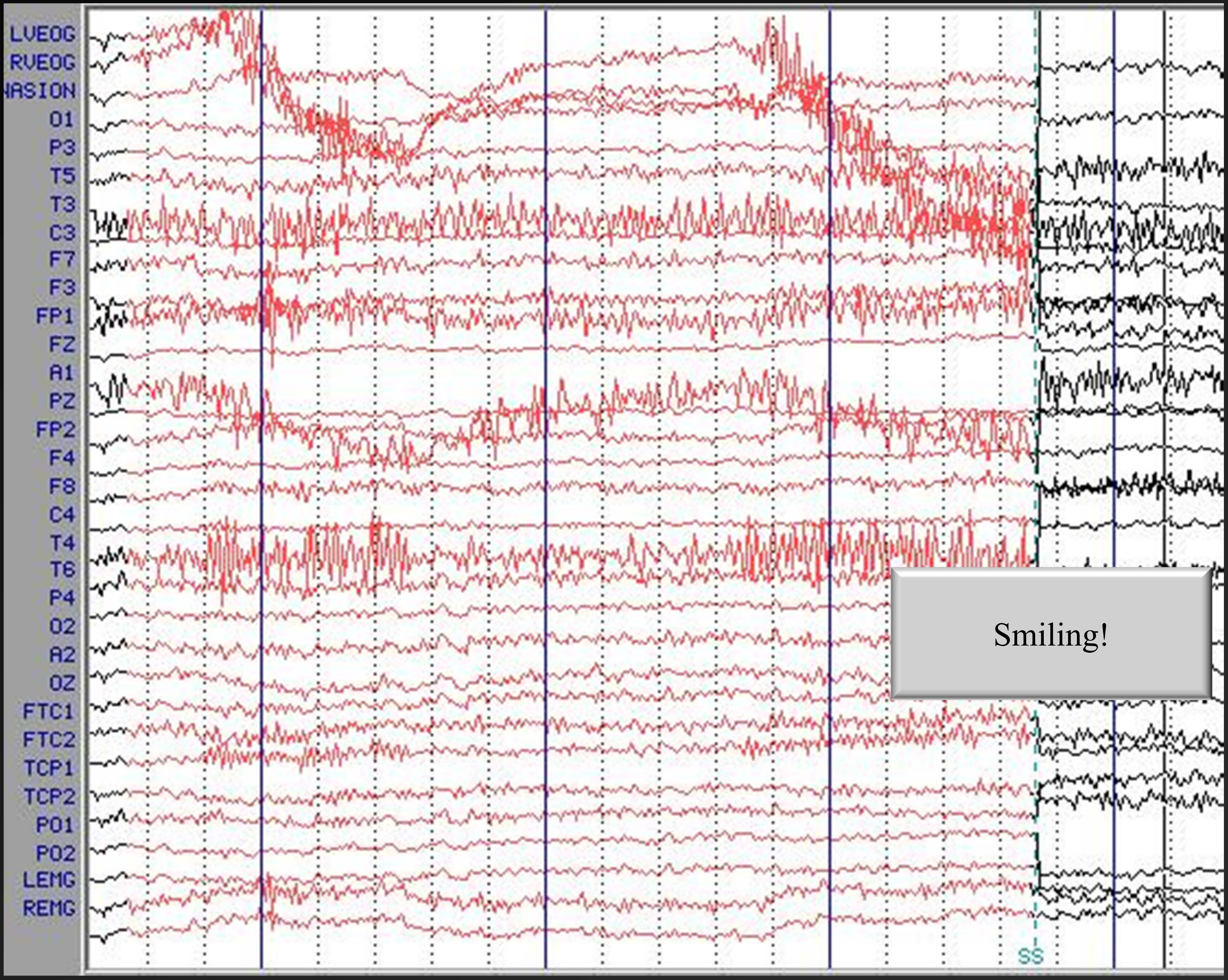
T3
C3
F7
F3
FP1
FZ
A1
PZ
FP2
F4
F8
C4
T4
T6
P4
O2
A2
OZ
FTC1
FTC2
TCP1
TCP2
PO1
PO2
LEMG
REMG
Muscle Burst


LVEOG
RVEOG
NASION
O1
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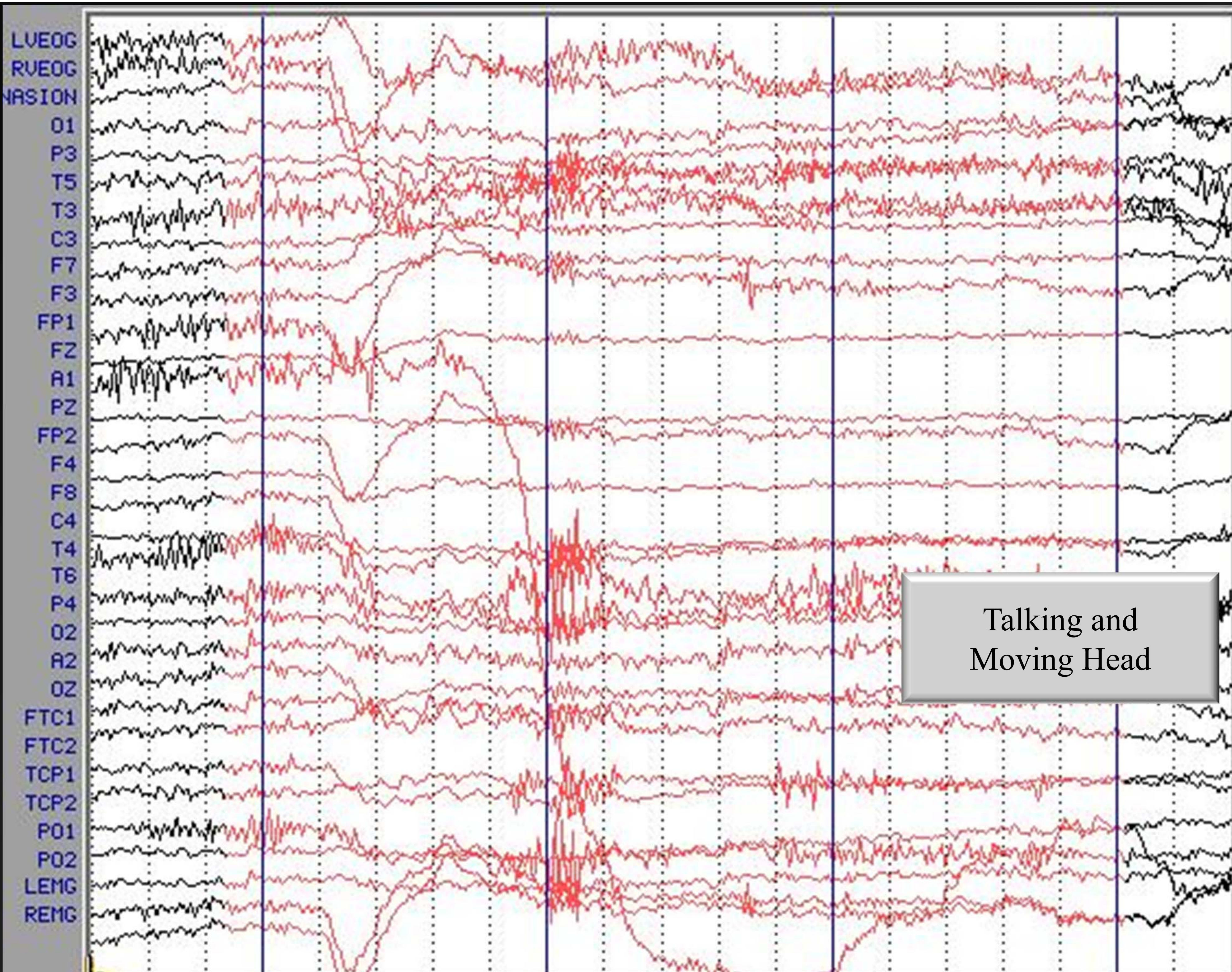
T3
C3
F7
F3
FP1
FZ
A1
PZ
FP2
F4
F8
C4
T4
T6
P4
O2
A2
OZ
FTC1
FTC2
TCP1
TCP2
PO1
PO2
LEMG
REMG
SS
Smiling!


LVEOG
RVEOG
NASION
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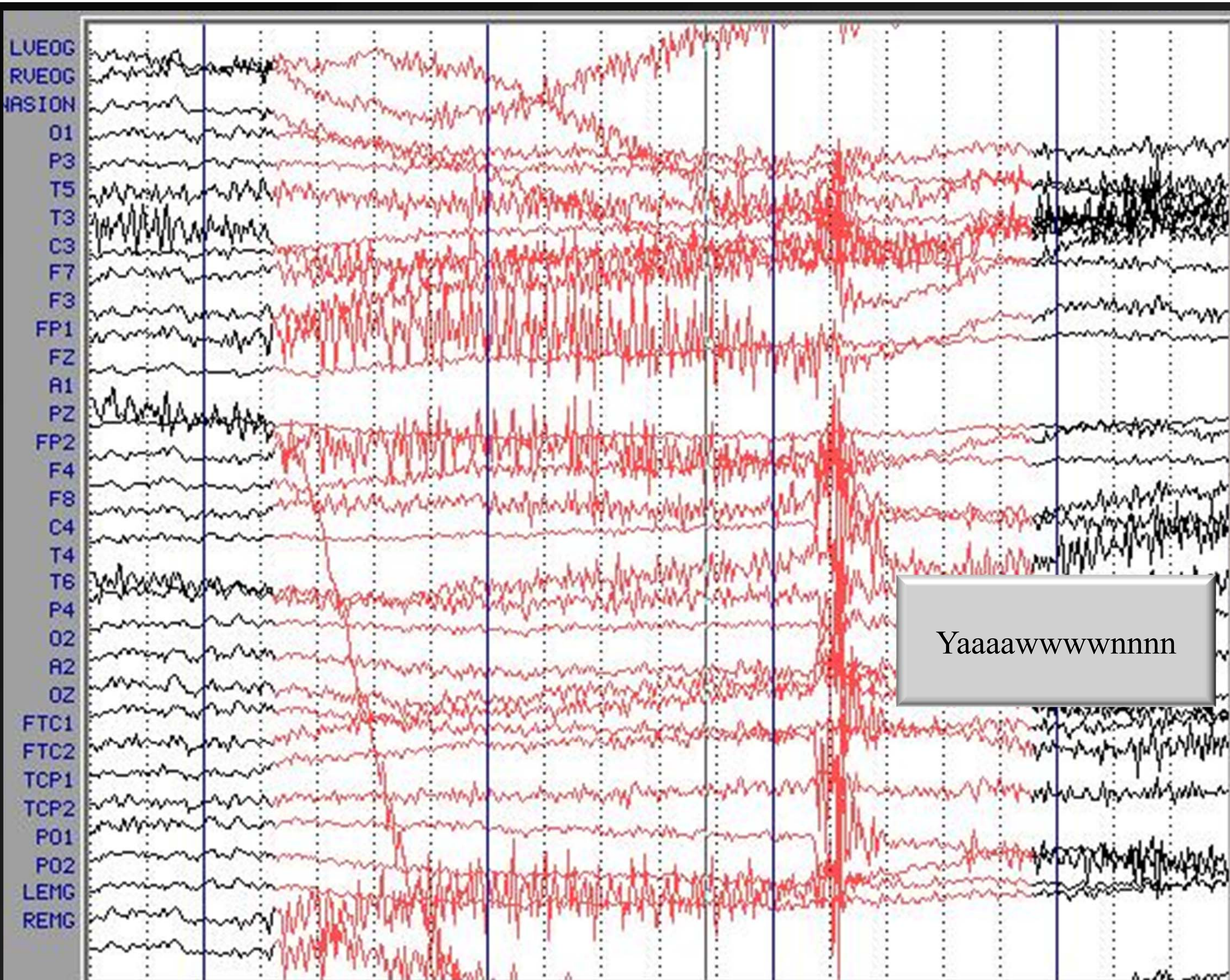
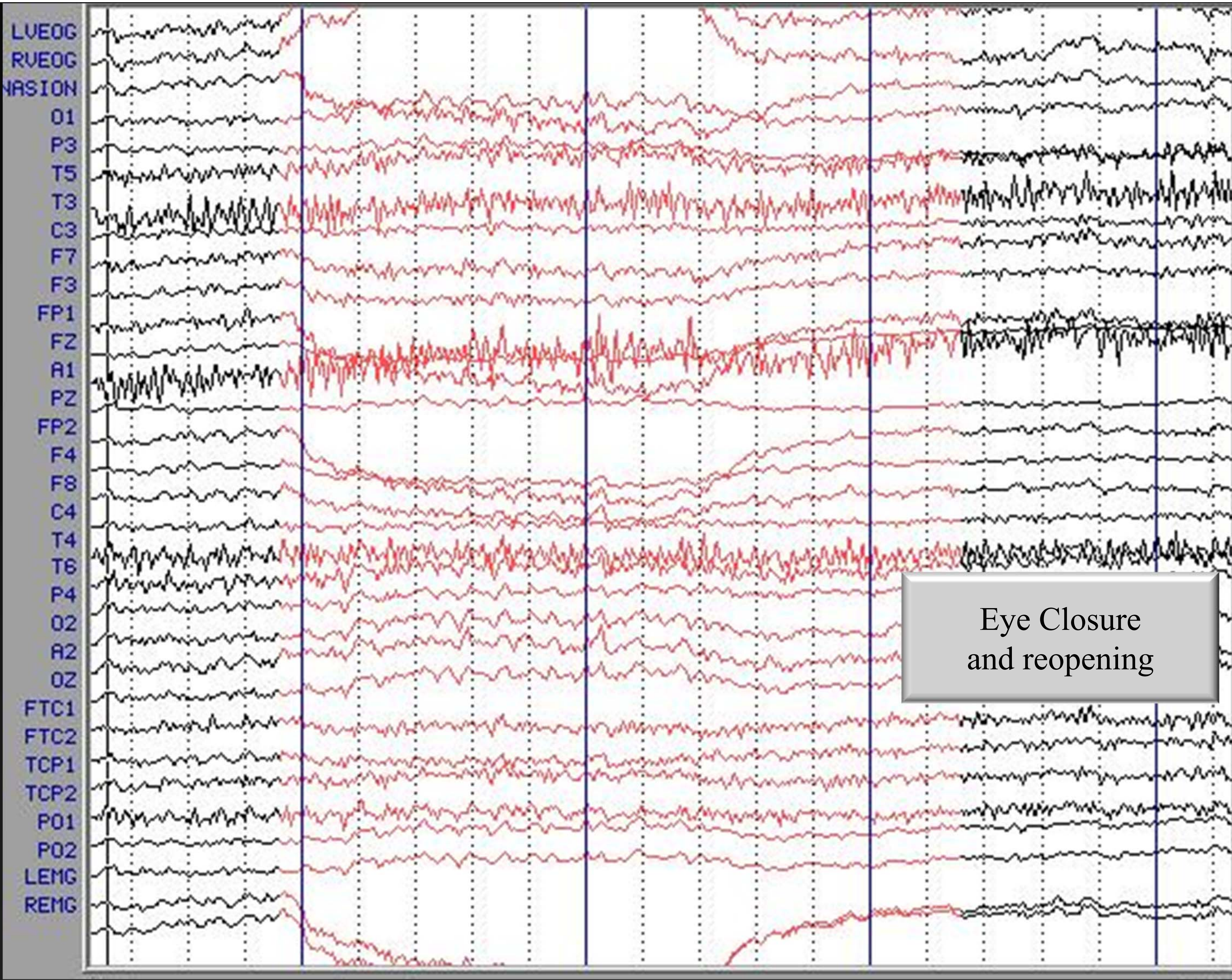
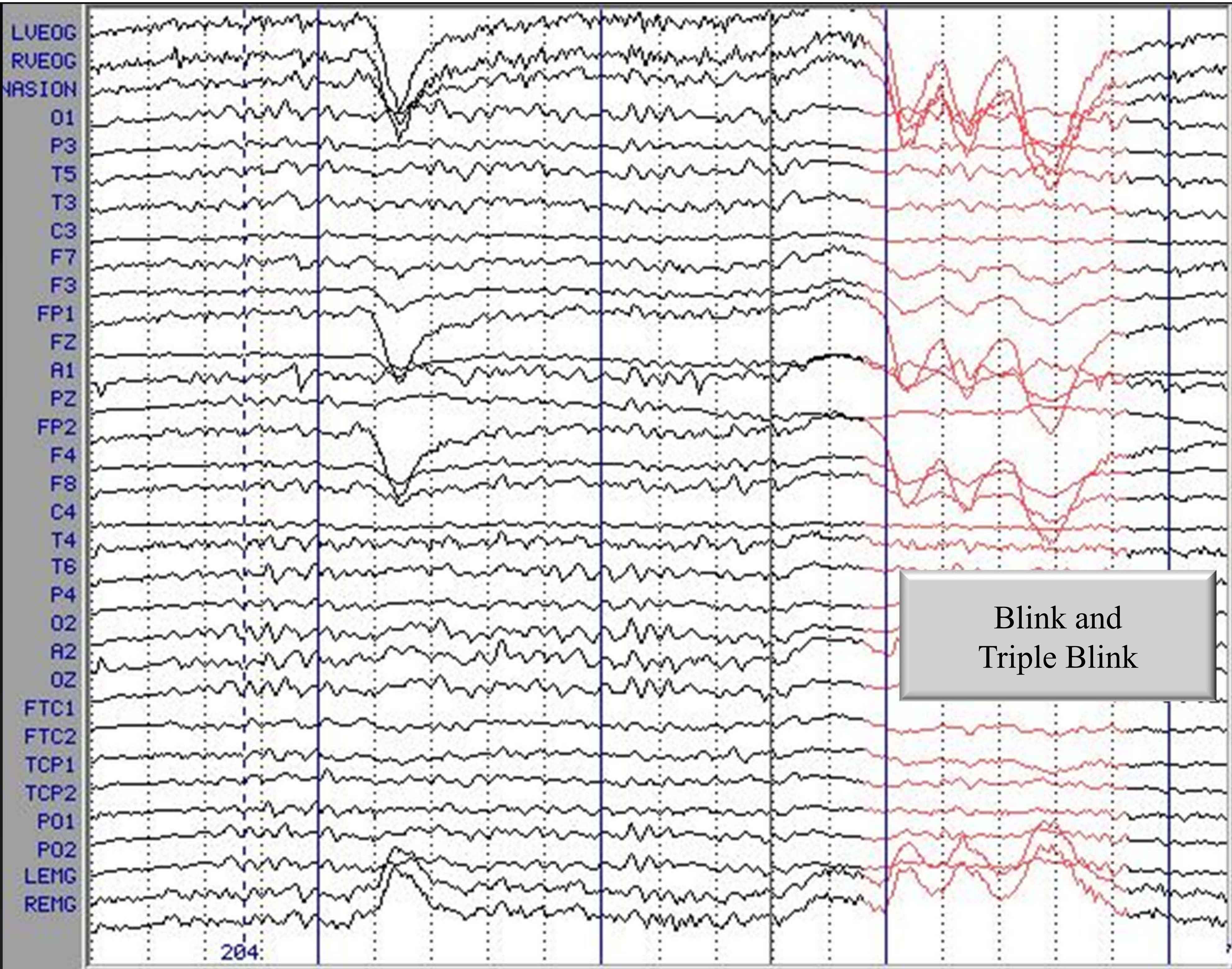
C3
F7
F3
FP1
FZ
A1
PZ
FP2
F4
F8
C4
T4
T6
P4
O2
A2
OZ
FTC1
FTC2
TCP1
TCP2
PO1
PO2
LEMG
REMG
Talking and Moving Head


LVEOG
RVEOG
NASION
O1
P3
T5
T3
C3
F7
F3
FP1
FZ
A1
PZ
FP2
F4
F8
C4
T4
T6
P4
O2
A2
OZ
FTC1
FTC2
TCP1
TCP2
PO1
PO2
LEMG
REMG
Yaaaawwwwnnnn



LVEOG
RVEOG
NASION
O1
P3
T5
T3
C3
F7
F3
FP1
FZ
A1
PZ
FP2
F4
F8
C4
T4
T6
P4
O2
A2
OZ
FTC1
FTC2
TCP1
TCP2
PO1
PO2
LEMG
REMG
Eye Closure
and reopening


LVEOG
RVEOG
NASION
O1
P3
T5
T3
C3
F7
F3
FP1
FZ
A1
PZ
FP2
F4
F8
C4
T4
T6
P4
O2
A2
OZ
FTC1
FTC2
TCP1
TCP2
PO1
PO2
LEMG
REMG
204
Blink and
Triple Blink

Demo – real live EEG

AC Signal Recording Options

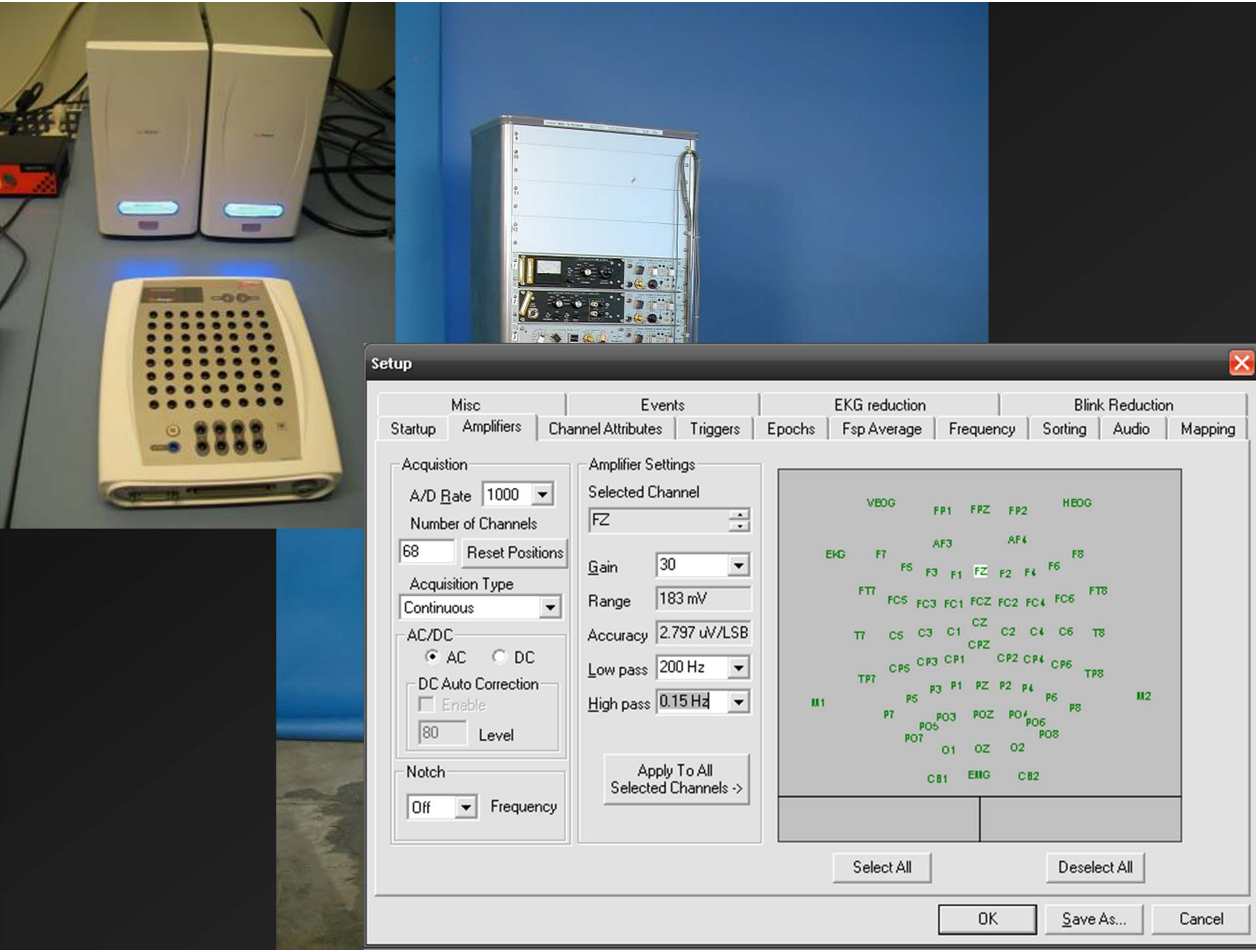
- Time Constant/HP filter
  - Low frequency cutoff is related to TC by:

$$F = \frac{1}{(2\pi(TC))}$$

Where F = frequency in Hz, TC = Time Constant in Seconds

Applying formula:

Time Constant (sec)	Frequency (Hz)
10.00	.016
5.00	.032
1.00	.159
.30	.531
.10	1.592
.01	15.915


Setup
Misc
Events
EKG reduction
Blink Reduction
Startup
Amplifiers
Channel Attributes
Triggers
Epochs
Fsp Average
Frequency
Sorting
Audio
Mapping
Acquistion
A/D Rate
1000
Number of Channels
68
Reset Positions
Acquisition Type
Continuous
AC/DC
AC
DC
DC Auto Correction
Enable
80
Level
Notch
Off
Frequency
Amplifier Settings
Selected Channel
FZ
Gain
30
Range
183 mV
Accuracy
2.797 uV/LSB
Low pass
200 Hz
High pass
0.15 Hz
Apply To All
Selected Channels ->
VEOG
FP1
FPZ
FP2
HEOG
AF3
AF4
EKG
F7
F5
F3
F1
FZ
F2
F4
F6
F8
FT7
FC5
FC3
FC1
FCZ
FC2
FC4
FC6
FT8
T7
C5
C3
C1
CZ
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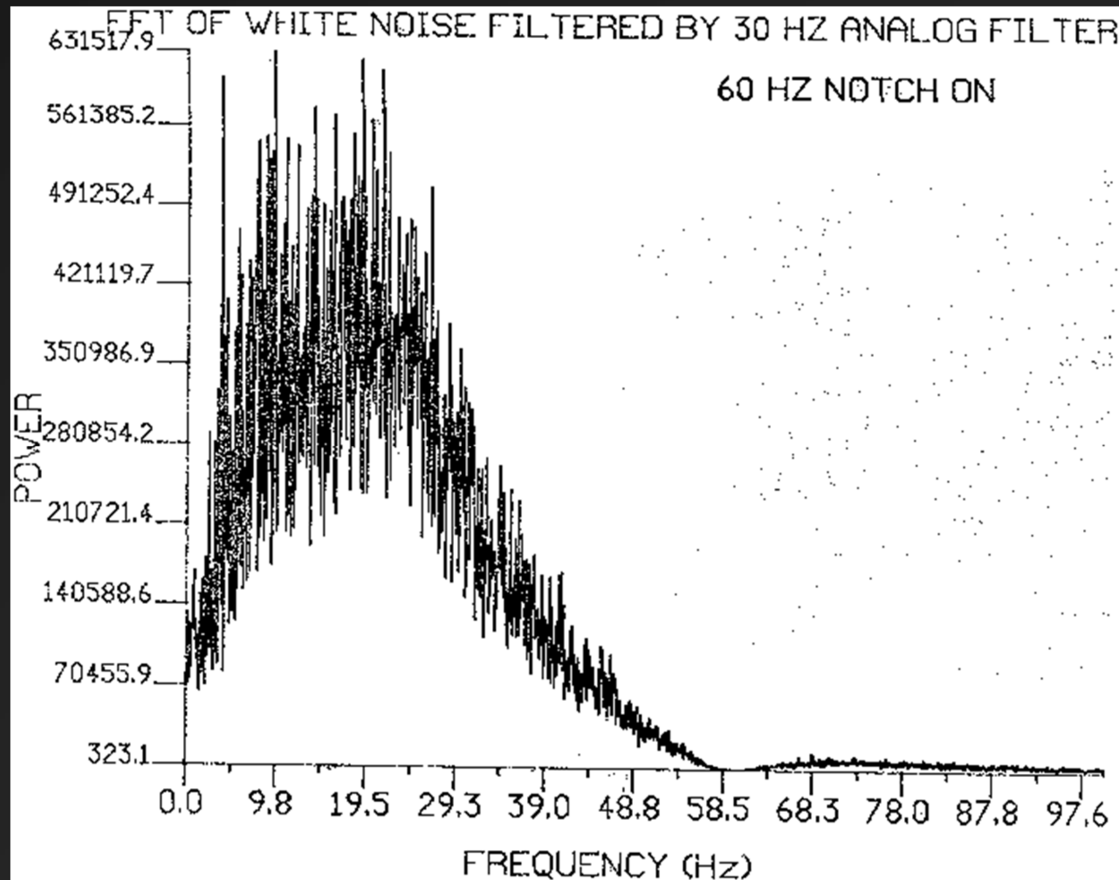
C4
C6
T8
CPZ
CP5
CP3
CP1
CP2
CP4
CP6
TP7
TP8
M1
P5
P3
P1
PZ
P2
P4
P6
P8
M2
P7
PO5
PO3
POZ
PO4
PO6
PO7
PO8
O1
OZ
O2
CB1
EMG
CB2
Select All
Deselect All
OK
Save As...
Cancel

Hi Frequency/LP Settings

- Do not eliminate frequencies of interest
- Polygraphs have broad roll-off characteristics
- Be mindful of digitization rate (more info soon!)



Digital Signal Acquisition

- Analog Vs Digital Signals
  - Analog
    - Continuously varying voltage as fxn of time
  - Discrete Time
    - Discrete points on time axis, but full range in amplitude
  - Digital
    - Discrete time points on x axis represented as a limited range of values (usally 2^x, e.g $2^{12} = 4096$)

A/D converters

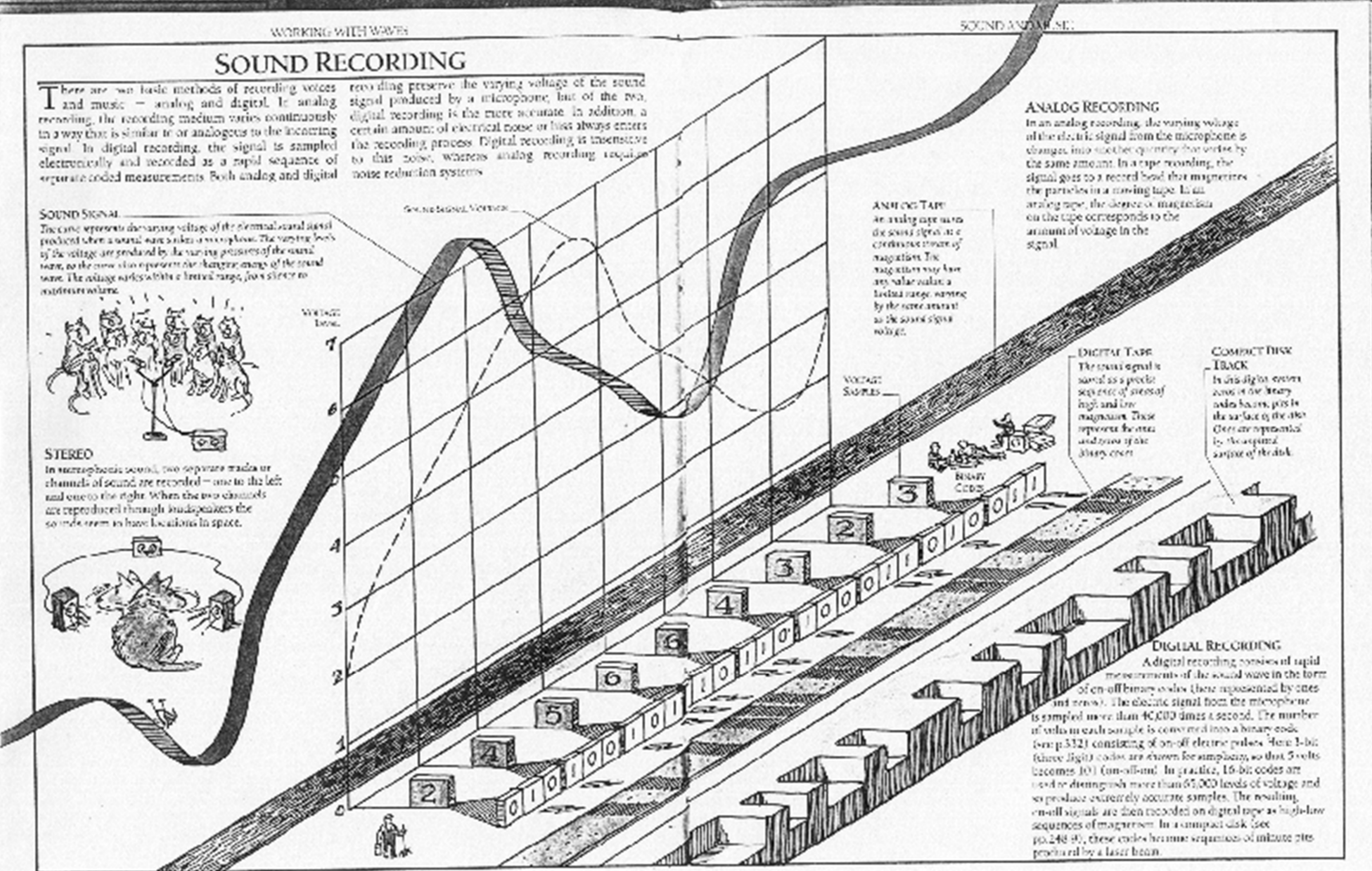
- Schmidt Trigger as simple example
- The A/D converter (Schematic diagram)
  - Multiplexing (several channels); A/D converter is serial processor
    - Result is a vector [1 x n samples] of digital values for each channel ([x(t0), x(t1), x(t2),...,x(tn-1)]
  - 12 bit converters allow 212 = 4096 values
  - 16 bit converters allow 216 = 65536 values

- 12 bit is adequate for EEG
  - 4096 values allow 1 value for each ~0.02 µvolts of scalp voltage (depending upon sensitivity of amplifier, which will amplify signal ~20,000 times before polygraph output)
  - e.g.,
    - 2.1130 µvolts => 2481 D.U.'s (2480.74)
    - 2.1131 µ volts => 2481 D.U.'s (2480.76)
    - 2.1250 µ volts => 2483 D.U.'s (2483.20)

FPT ISBN 0-395-42857-2 3425.35

SOUND RECORDING

There are two basic methods of recording voices and music – analog and digital. In analog recording, the recording medium varies continuously in a way that is similar to or analogous to the incoming signal. In digital recording, the signal is sampled electronically and recorded as a rapid sequence of separate coded measurements. Both analog and digital recording preserve the varying voltage of the sound signal produced by a microphone, but of the two, digital recording is the more accurate. In addition, a certain amount of electrical noise or hiss always enters the recording process. Digital recording is insensitive to this noise, whereas analog recording requires noise reduction systems.



SOUND SIGNAL

The curve represents the varying voltage of the electrical sound signal produced when a sound wave strikes a microphone. The varying levels of the voltage are produced by the varying pressures of the sound wave, so the curve also represents the changing energy of the sound wave. The voltage varies within a limited range, from silence to maximum volume.

STEREO

In stereophonic sound, two separate tracks or channels of sound are recorded – one to the left and one to the right. When the two channels are reproduced through loudspeakers the sounds seem to have locations in space.

ANALOG TAPE

An analog tape saves the sound signal as a continuous stream of magnetism. The magnetism may have any value within a limited range, varying by the same amount as the sound signal voltage.

ANALOG RECORDING

In an analog recording, the varying voltage of the electric signal from the microphone is changed into another quantity that varies by the same amount. In a tape recording, the signal goes to a record head that magnetizes the particles in a moving tape. In an analog tape, the degree of magnetism on the tape corresponds to the amount of voltage in the signal.

DIGITAL TAPE

The sound signal is saved as a precise sequence of areas of high and low magnetism. These represent the ones and zeros of the binary codes.

COMPACT DISK TRACK

In this digital system, zeros in the binary codes become pits in the surface of the disk. Ones are represented by the original surface of the disk.

DIGITAL RECORDING

A digital recording consists of rapid measurements of the sound wave in the form of on-off binary codes (here represented by ones and zeros). The electric signal from the microphone is sampled more than 40,000 times a second. The number of volts in each sample is converted into a binary code (see p.332) consisting of on-off electric pulses. Here 3-bit (three digit) codes are shown for simplicity, so that 5 volts becomes 101 (on-off-on). In practice, 16-bit codes are used to distinguish more than 65,000 levels of voltage and so produce extremely accurate samples. The resulting on-off signals are then recorded on digital tape as high-low sequences of magnetism. In a compact disk (see pp.248-9), these codes become sequences of minute pits produced by a laser beam.

The Problem of Aliasing

- Definition
  - To properly represent a signal, you must sample at a fast enough rate.
  - Nyquist's (1928) theorem
    - a sample rate twice as fast as the highest signal frequency will capture that signal perfectly
    - Stated differently, the highest frequency which can be accurately represented is one-half of the sampling rate
    - This frequency has come to be known as the Nyquist frequency and equals ½ the sampling rate
- Comments
  - Wave itself looks distorted, but frequency is captured adequately.
  - Frequencies faster than the Nyquist frequency will not be adequately represented
  - Minimum sampling rate required for a given frequency signal is known as Nyquist sampling rate

Harry Nyquist

Aliasing and the Nyquist Frequency

- In fact, frequencies above Nyquist frequency represented as frequencies lower than Nyquist frequency
  - F_{Ny} + x Hz will be seen as F_{Ny} - x Hz
  - "folding back"
    - frequency $2F_{Ny}$ seen as 0,
    - frequency $3F_{Ny}$ will be seen as F_{Ny}
    - accordion-like folding of frequency axis

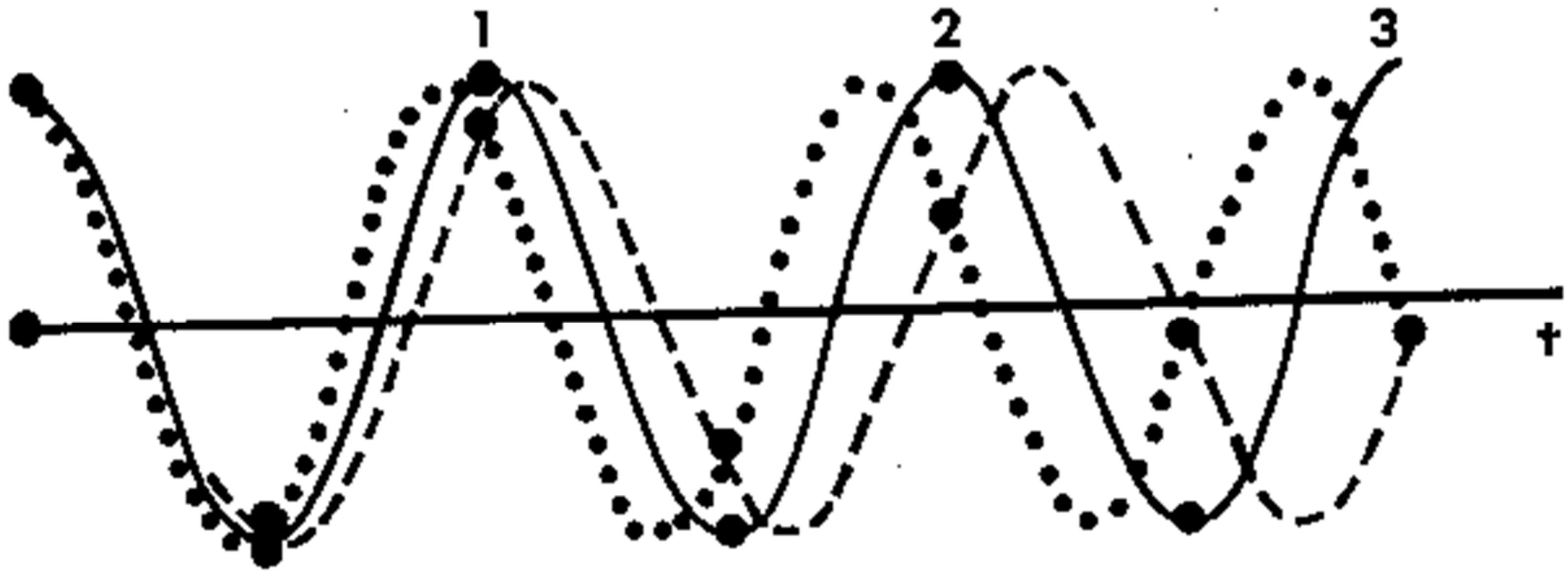


Fig. 3.1. A cosine wave of frequency F (solid line) sampled at its Nyquist rate. A higher frequency (dotted) wave, frequency F + a, is shown sampled at the same rate. At the sample times it is indistinguishable from a lower frequency (dashed) wave, frequency F − a.

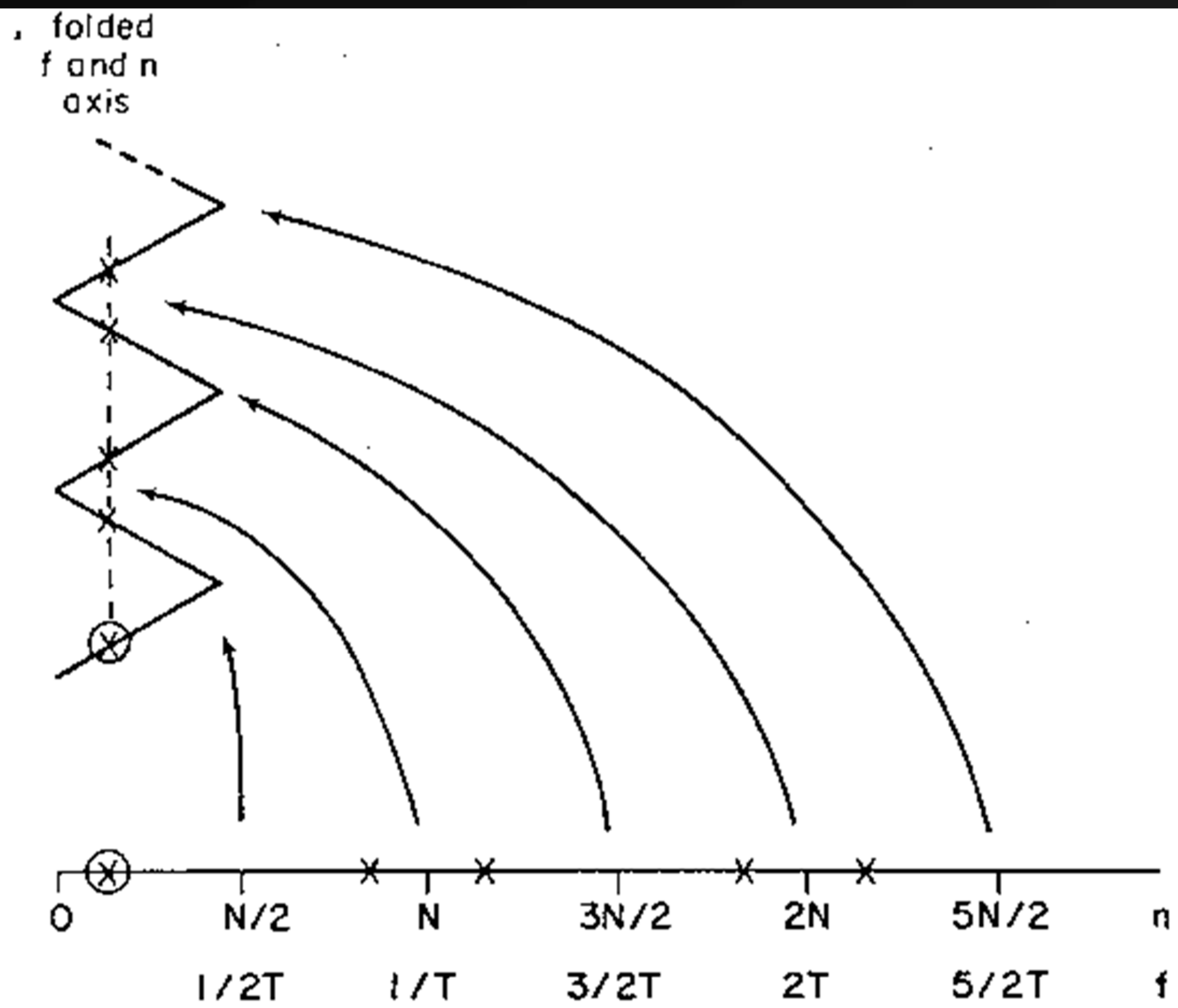
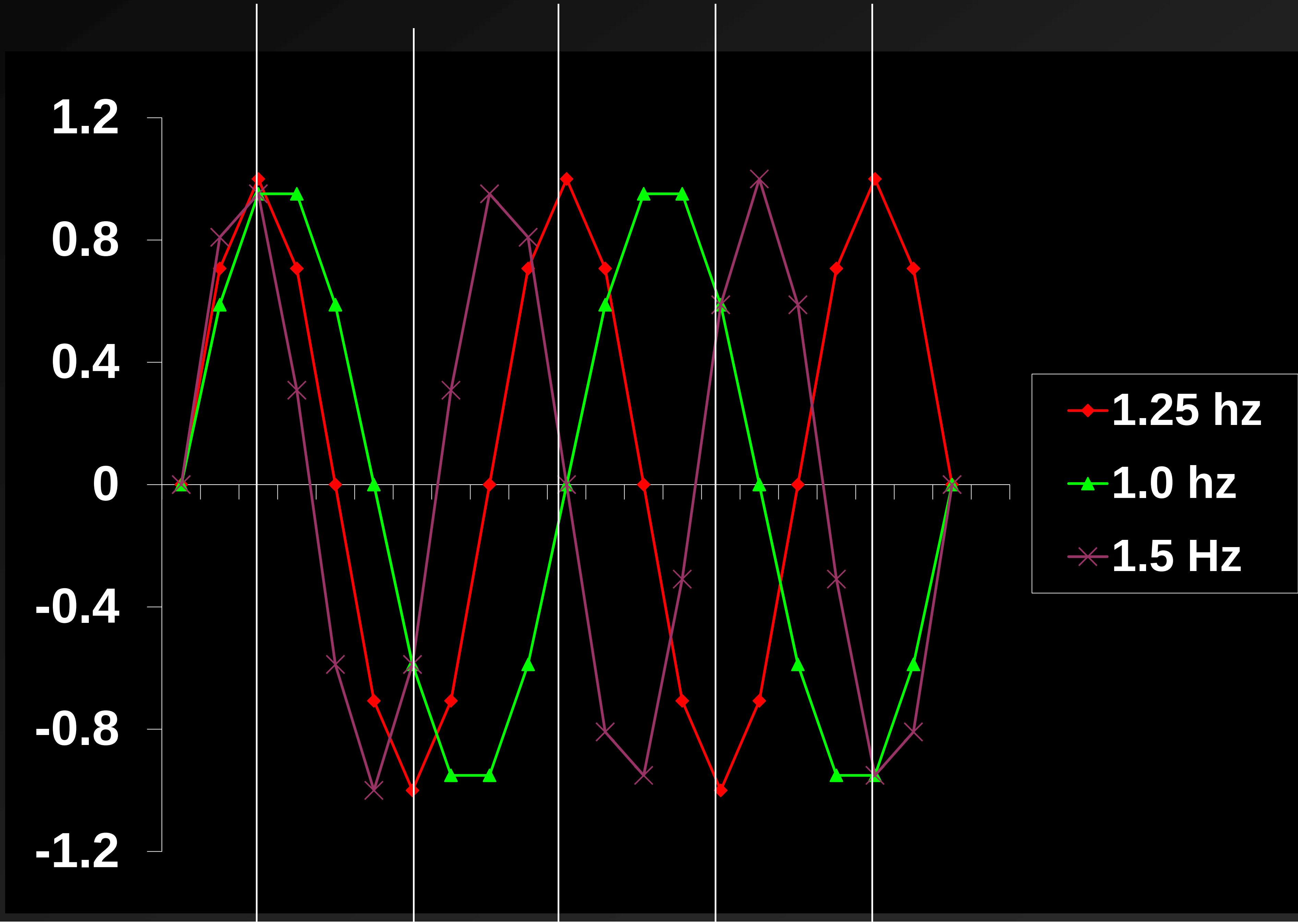
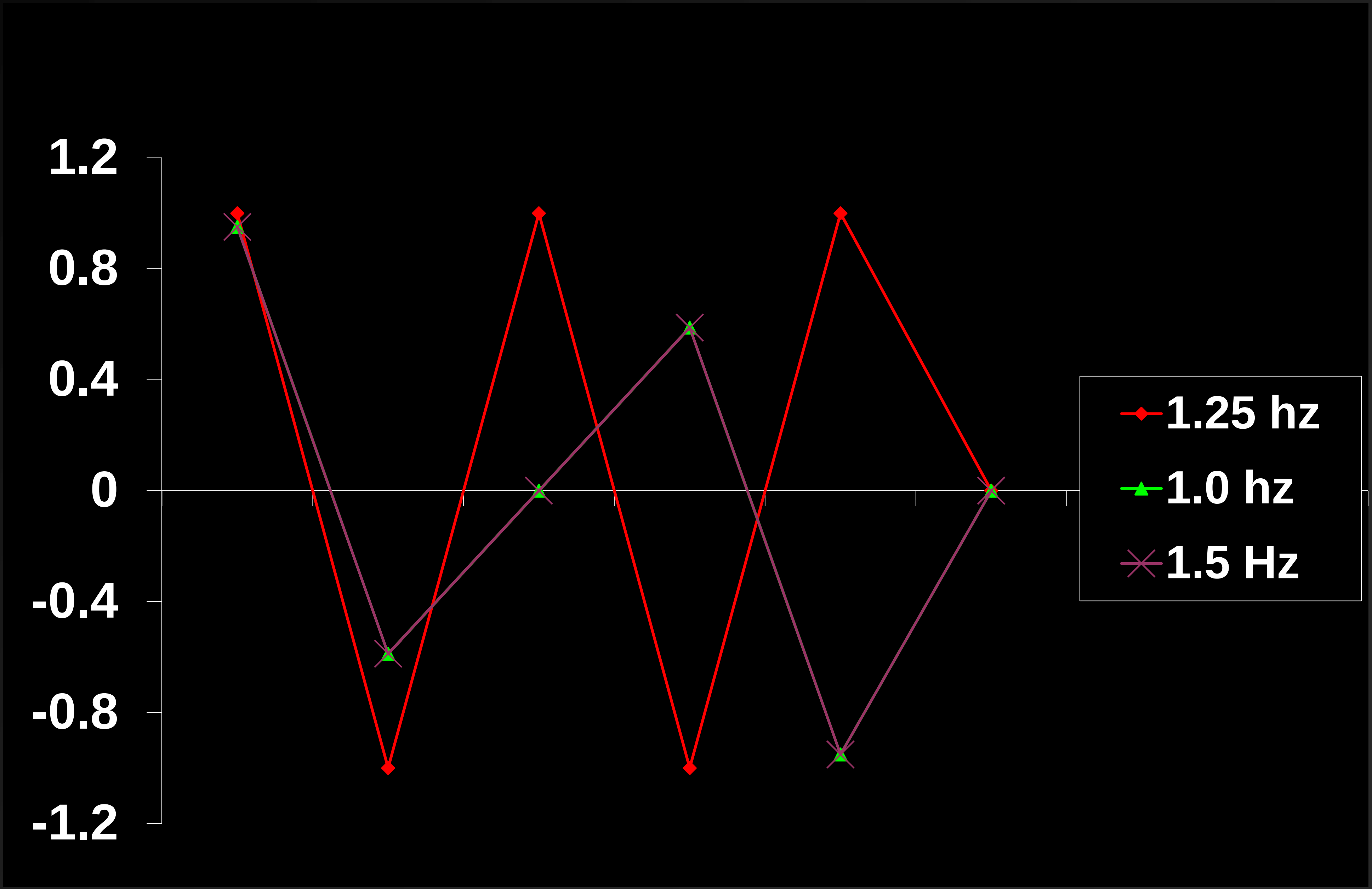


Fig. 3.2. The accordionlike folding of the frequency (or n) axis due to sampling of a continuous signal. Frequency components of the original signal marked with x's on the f axis are interpreted in the sampled version as belonging to the lowest frequency, an encircled x.

Aliasing Demo (Part 1, 10 Hz Sampling Rate)



Aliasing Demo (Part 2, 2.5 Hz Sampling Rate)



Solutions to Aliasing

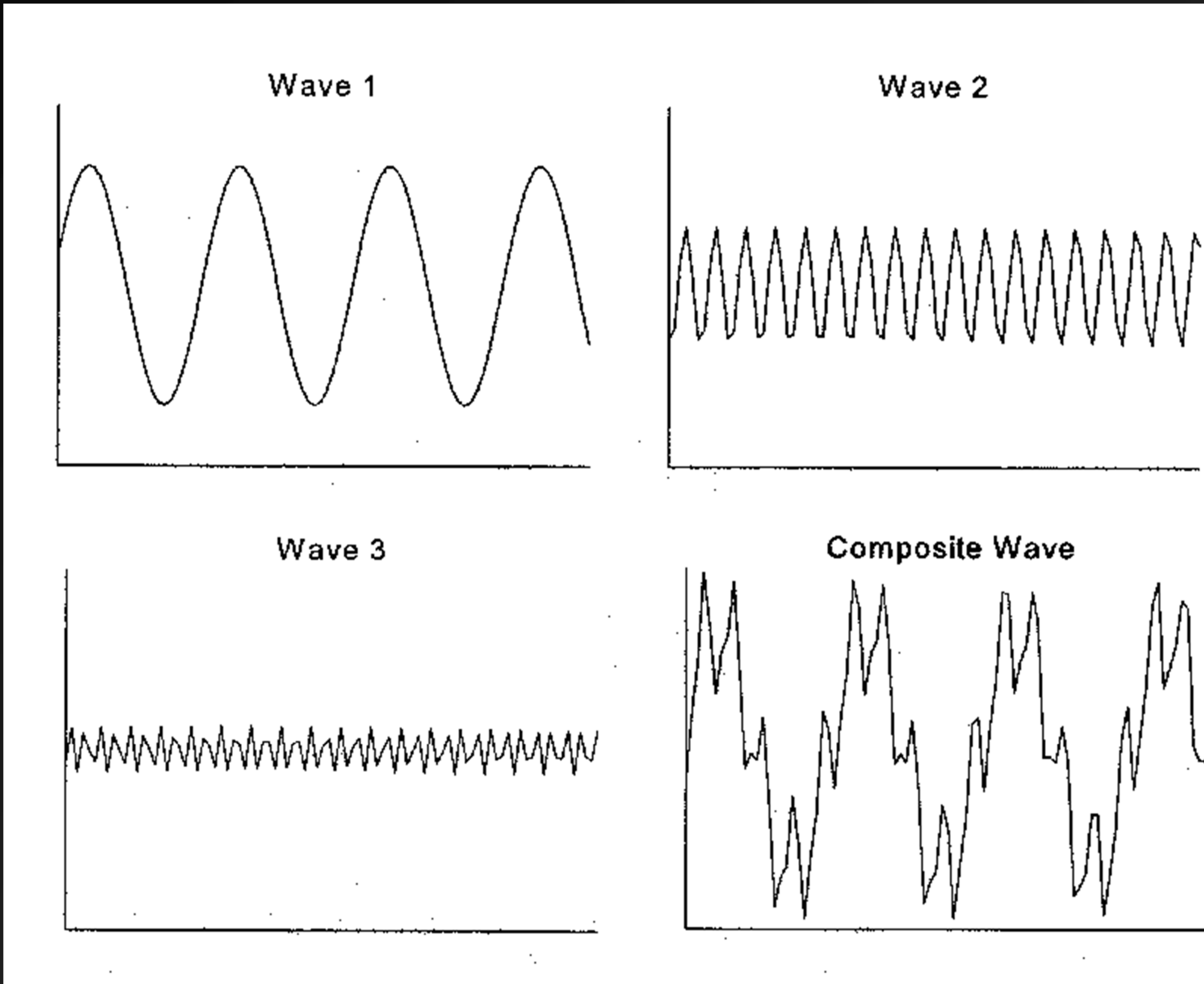
- Sample very fast
- Use anti-aliasing filters
- KNOW YOUR SIGNAL!

Time Domain Vs Frequency Domain Analysis

- Time Domain Analysis involves viewing the signal as a series of voltages as a function of time, [x(0), x(t1), x(t2),...,x(tn-1)]
  - e.g., skin conductance response, event-related potential
  - Relevant dependent variables
    - latency of a particular response
    - amplitude of that response within the time window
- More about time domain next time

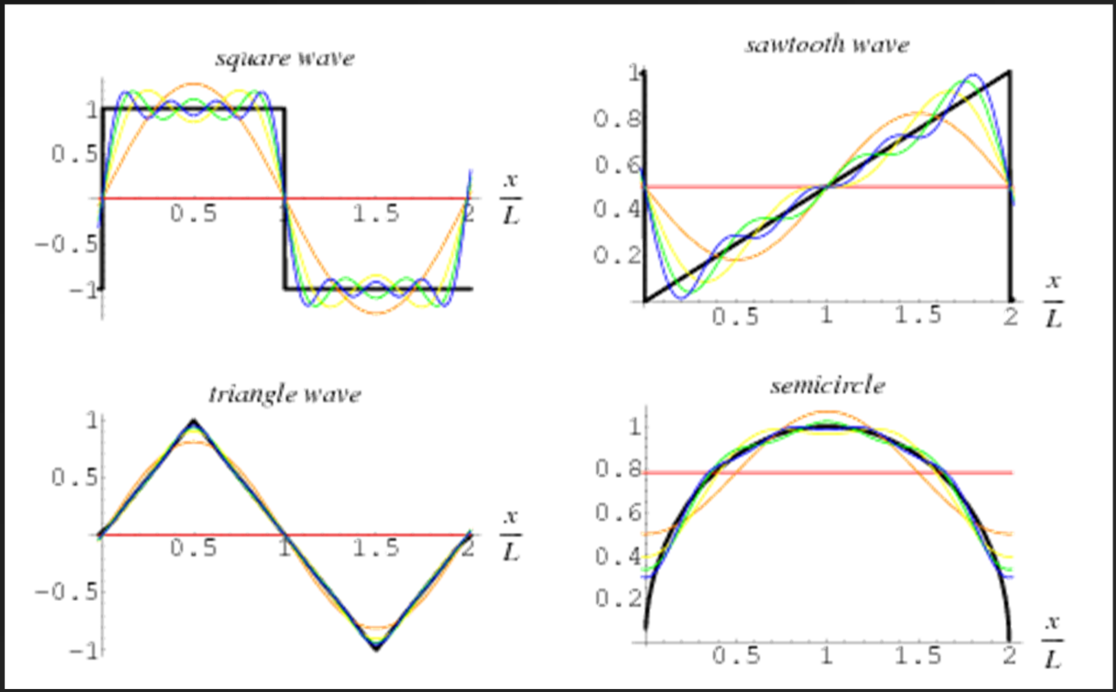
Time Domain Vs Frequency Domain Analysis

- Frequency Domain Analysis involves characterizing the signal in terms of its component frequencies
  - Assumes periodic signals
- Periodic signals (definition):
  - Repetitive
  - Repetitive
  - Repetition occurs at uniformly spaced intervals of time
- Periodic signal is assumed to persist from infinite past to infinite future


Wave 1
Wave 2
Wave 3
Composite Wave

Fourier Series Representation

- If a signal is periodic, the signal can be expressed as the sum of sine and cosine waves of different amplitudes and frequencies
- This is known as the Fourier Series Representation of a signal



Fourier Series Representation

- If a signal is periodic, the signal can be expressed as the sum of sine and cosine waves of different amplitudes and frequencies
- This is known as the Fourier Series Representation of a signal
- In Conceptual (but mathematically imprecise) terms:

$$x(t) = \text{Phase}(t0) + \sum_{1}^{\frac{N}{2}} [\text{Amp}_{\cos} * \cos(\text{fxn}(n,t,T)) + \text{Amp}_{\sin} * \sin(\text{fxn}(n,t,T))]$$

Where

Where N=number of samples

T=period sampled by the N samples

n=frequency from 0 to Nyquist, in 1/T increments

Interactive Fourier!

- Web Applet

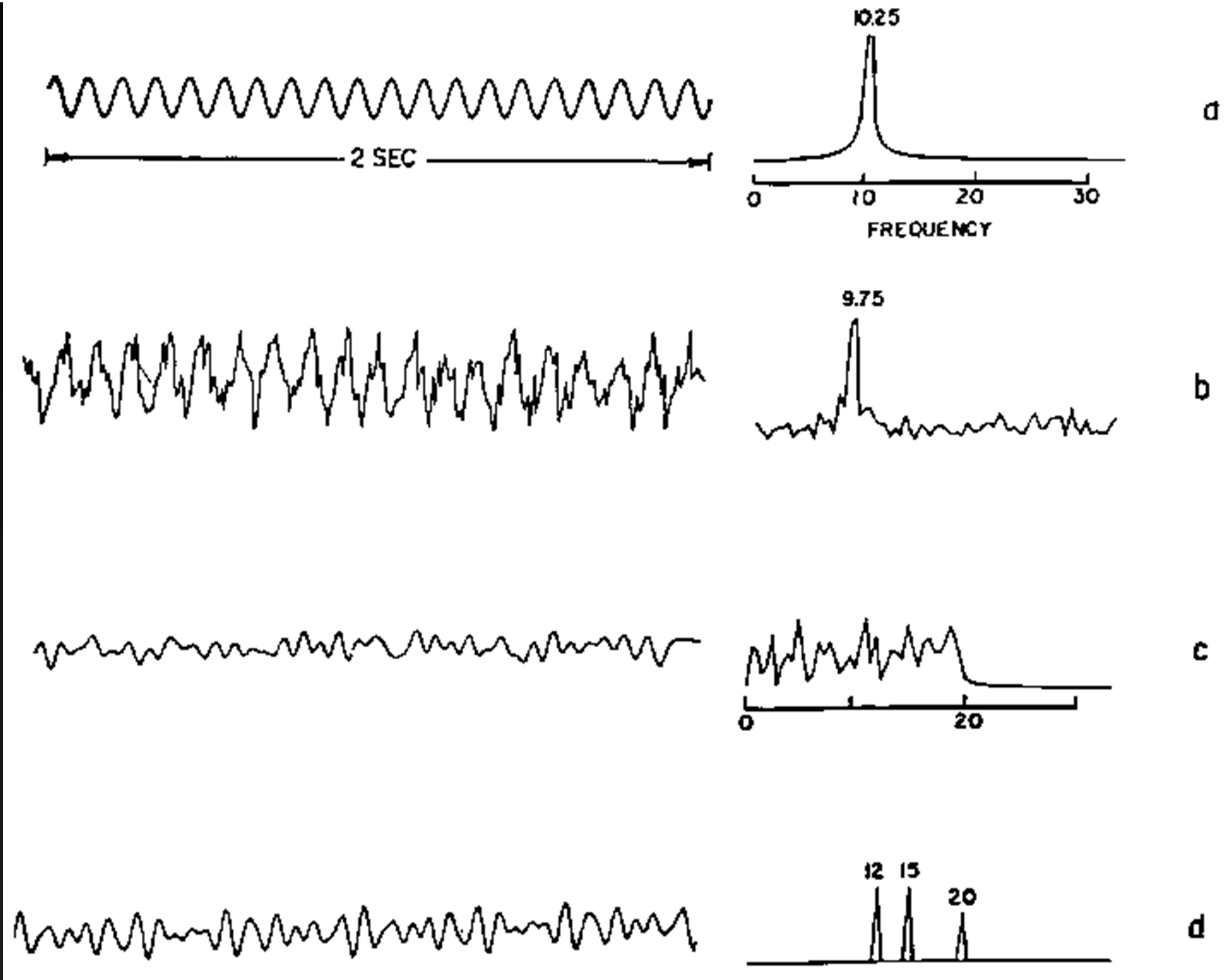
Fourier Series Representation

- Pragmatic Details
  - Lowest Fundamental Frequency is 1/T
  - Resolution is 1/T
- Phase and Power
  - There exist a phase component and an amplitude component to the Fourier series representation
    - Using both, it is possible to completely reconstruct the waveform.
- Psychophysiologist often interested in amplitude component:
  - Power spectrum; for each frequency n/T

$$|Amp_{cos}^2 + Amp_{sin}^2|$$

  - Amplitude Spectrum (may conform better to assumptions of statistical procedures); for each frequency n/T

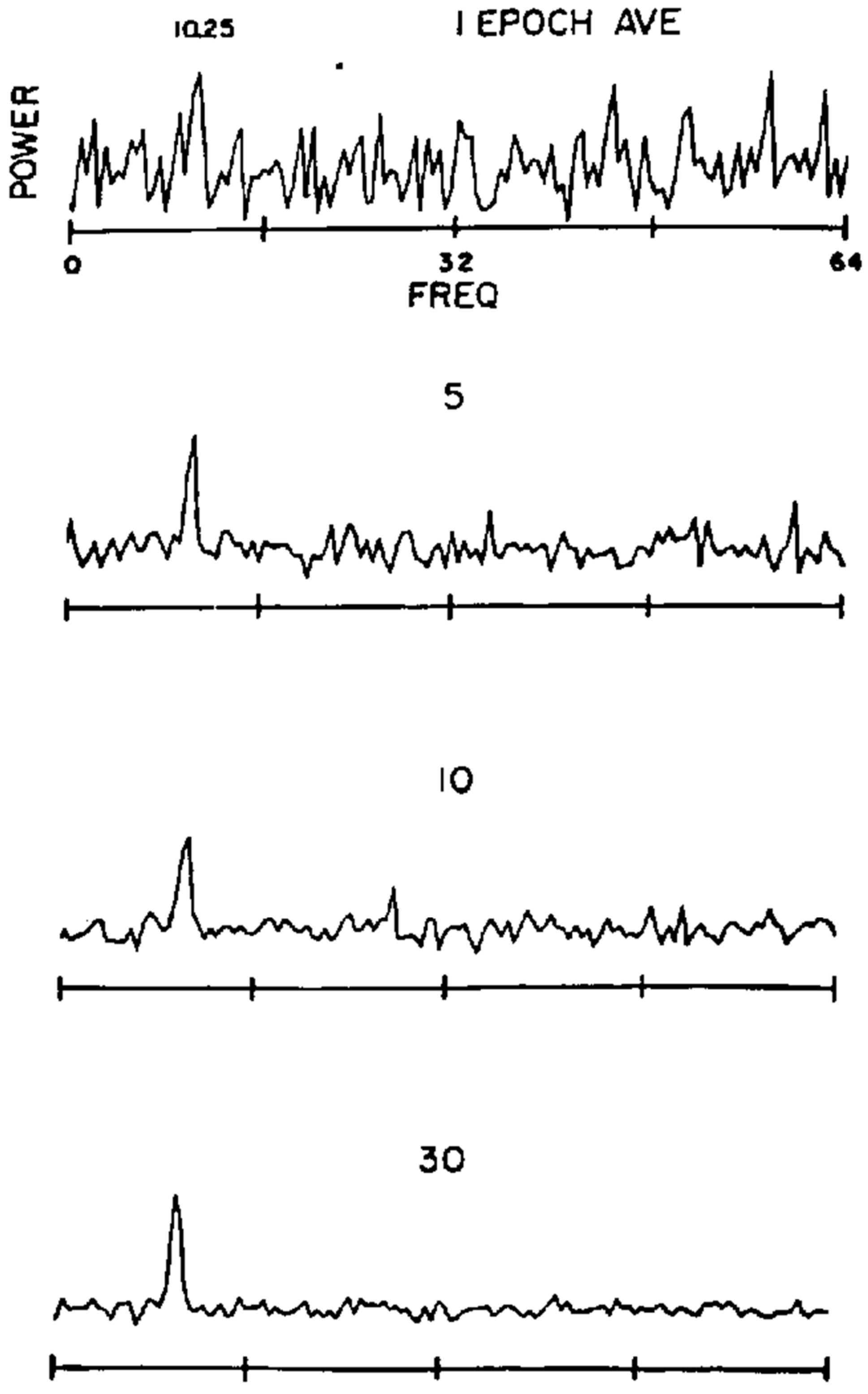
$$|Amp_{cos}^2 + Amp_{sin}^2|^{1/2}$$



Time Domain

Frequency Domain

Averaging Multiple Epochs improves ability to resolve signal

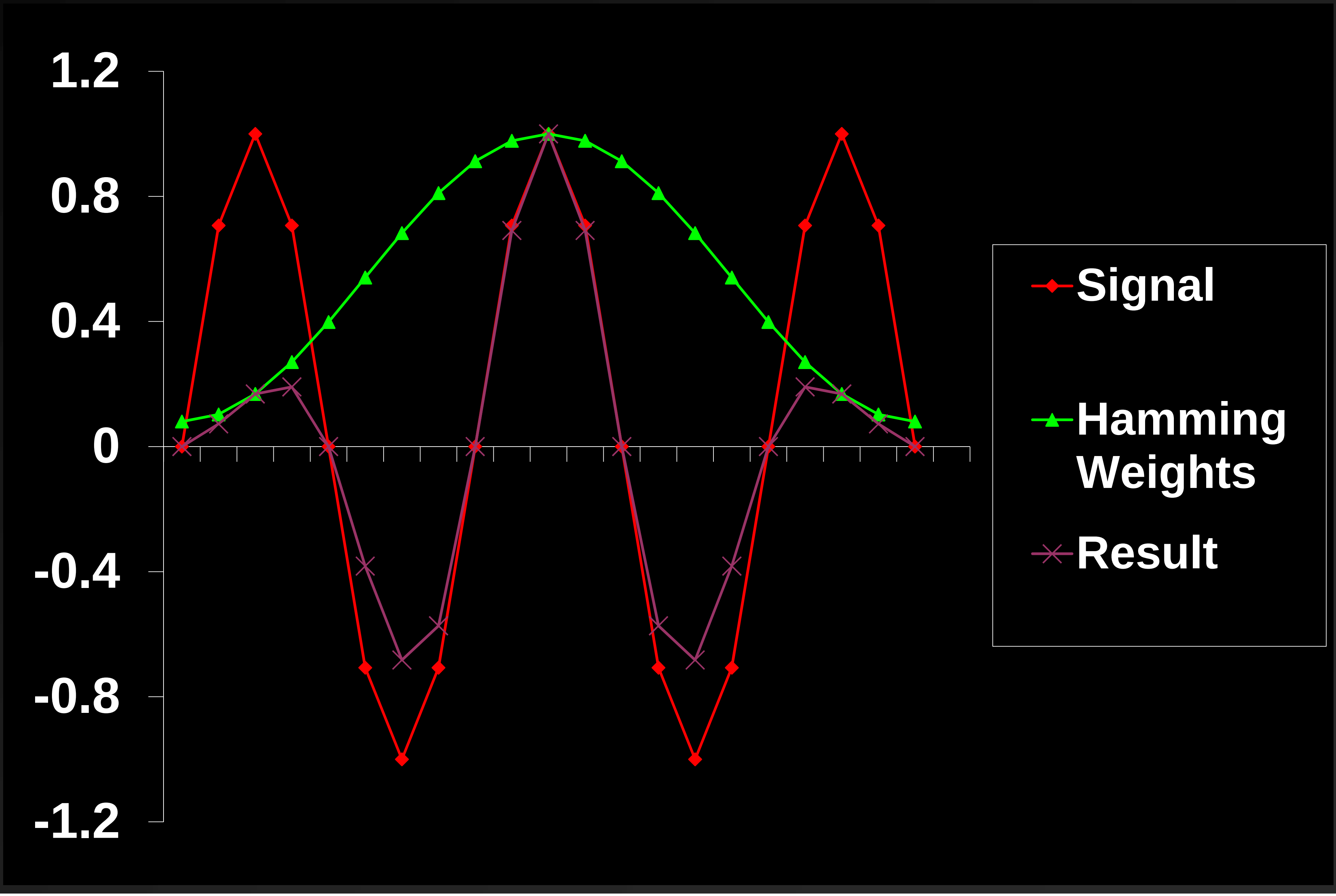


Note noise is twice amplitude of the signal

Lingering details

- In absence of phase information, it is impossible to reconstruct the original signal
  - **Infinite** number of signals that could produce the same amplitude or power spectrum
- Spectra most often derived via a **Fast** Fourier transform (FFT); a fourier transform of a discretely sampled band-limited signal with a power of 2 samples
- Sometimes **autocovariance function** is used (a signal covaries with itself at various phase lags; greater covariation at fundamental frequencies)
- Windowing: the Hamming Taper

Hamming Demo



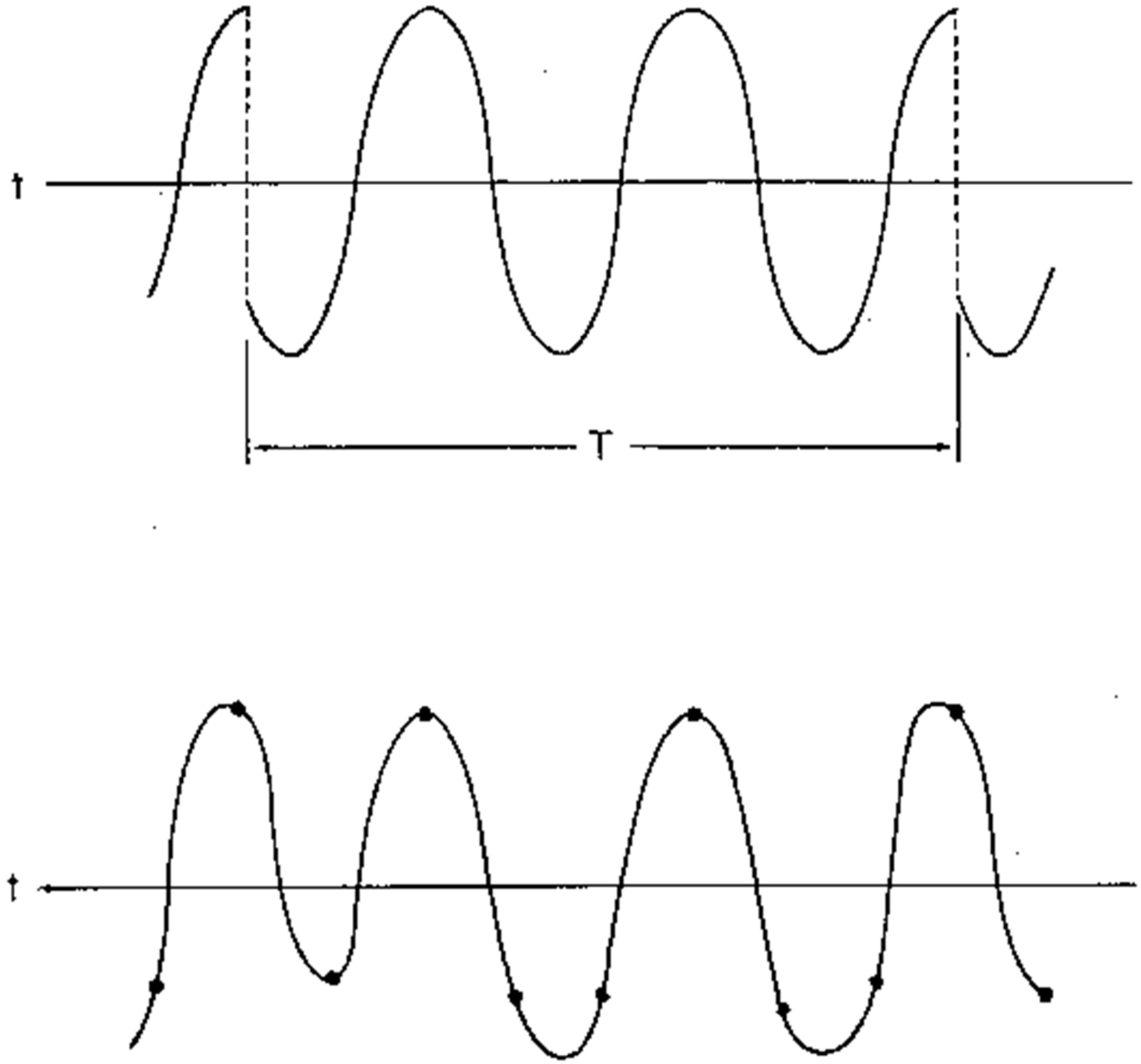
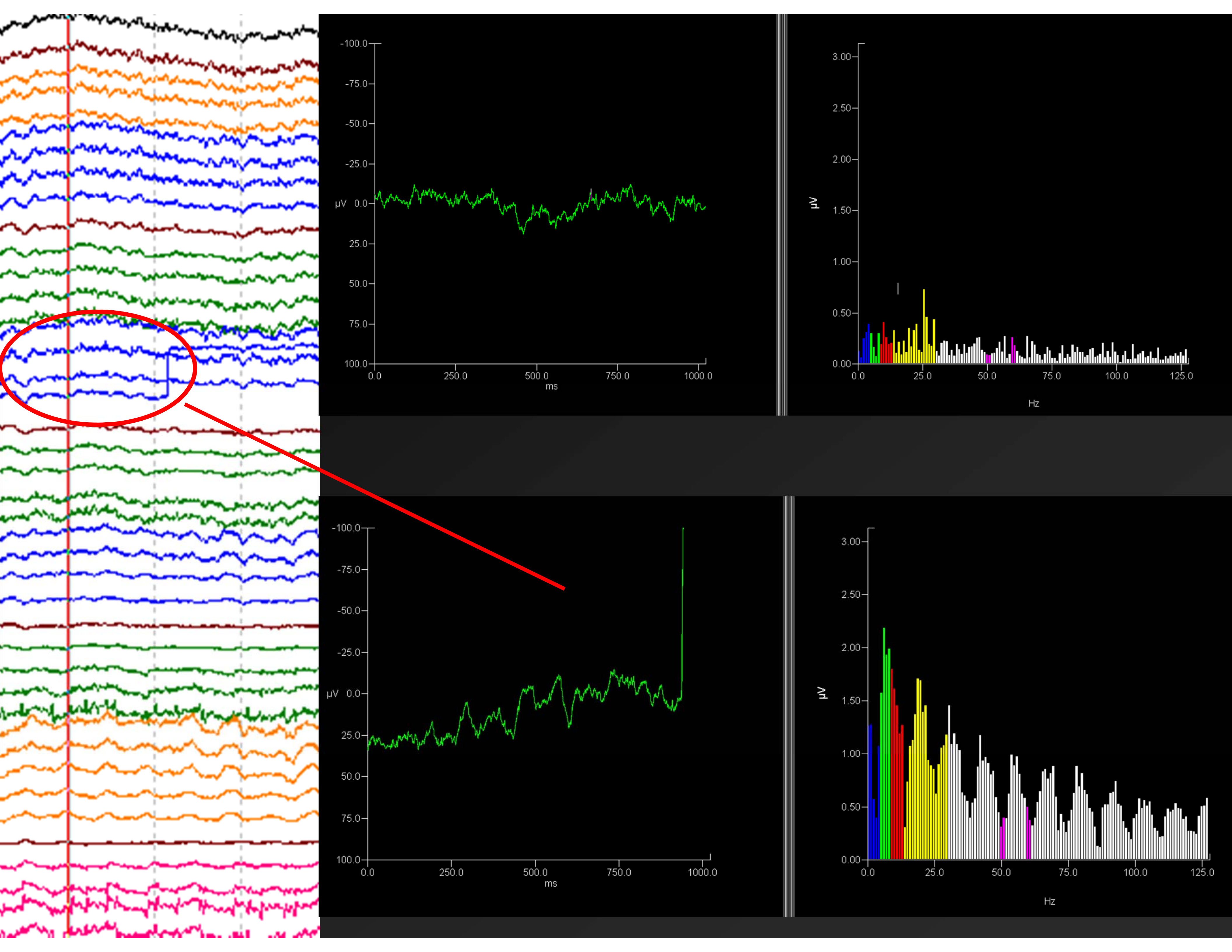


Fig. 3.3. Top, a periodicized segment of a cosine wave. T is the observation time and 3T/8 the period of the wave. Note the discontinuities at 0 and T. Bottom, a continuous and periodic band-limited wave drawn through the sample points Δ = T/16 sec apart.

Pragmatic Concerns

- Sample fast enough so no frequencies exceed Nyquist
  - signal bandwidth must be limited to less than Nyquist
  - Violation = ERROR
- Sample a long enough epoch so that lowest frequency will go through at least one period
  - Violation = ERROR
- Sample a periodic signal
  - if subject engaging in task, make sure that subject is engaged during entire epoch
  - Violation = ??, probably introduce some additional frequencies to account for change



-100.0
-75.0
-50.0
-25.0
µV 0.0
25.0
50.0
75.0
100.0
0.0
250.0
500.0
750.0
1000.0
ms
3.00
2.50
2.00
1.50
1.00
0.50
0.00
µV
0.0
25.0
50.0
75.0
100.0
125.0
Hz

Demo of EEG Data

- CNT Data to Frequency Domain Representation