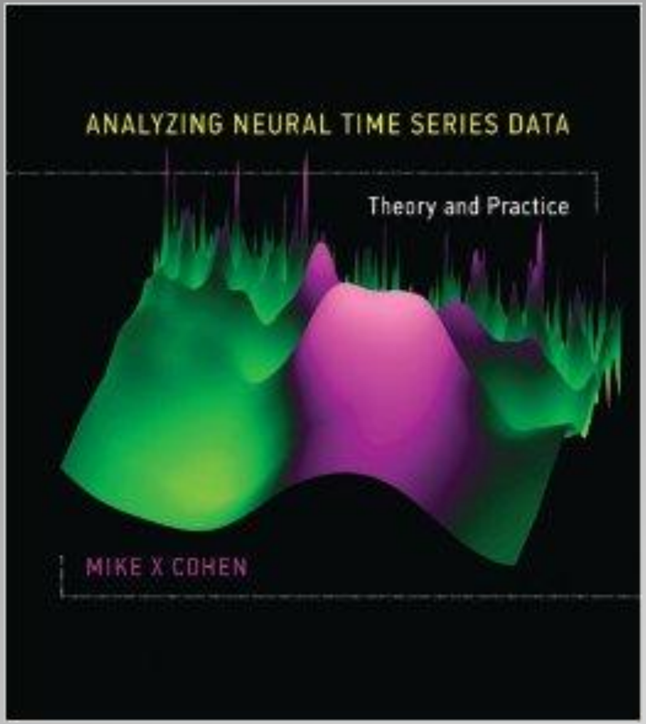
PSYC516:
Analyzing Neural Time-series Data

Spring, 2026
Mondays, 1^{00}-3^{45} p.m.
Room 323 Psychology

Course Resources Online:
https://psychophyslab.arizona.edu

Follow link to Courses



Available from:
Amazon:
http://www.amazon.com/gp/product/0262019876/ref=ox_ya_os_product
MIT Press:
https://mitpress.mit.edu/9780262019873/analyzing-neural-time-series-data/
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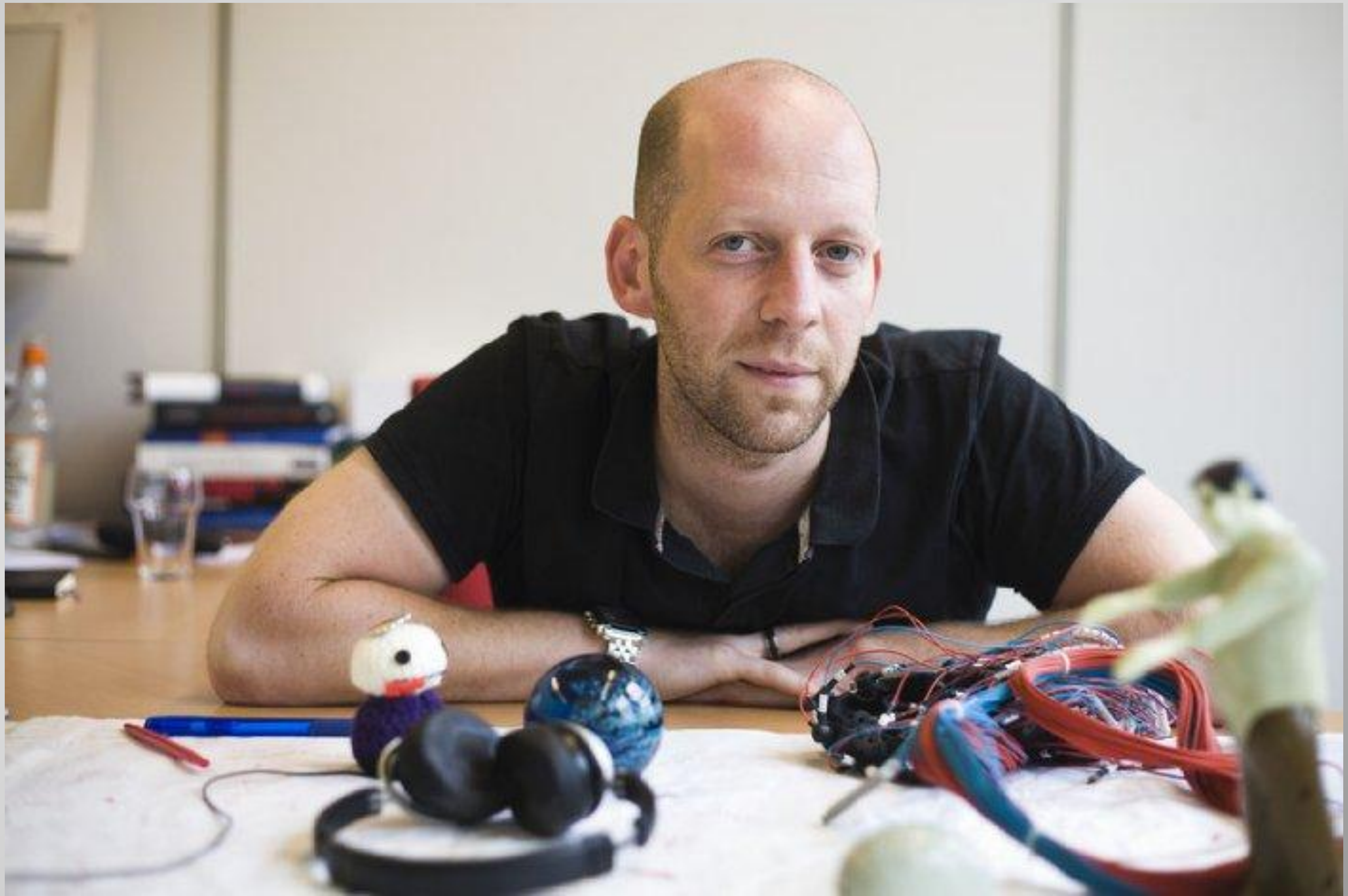
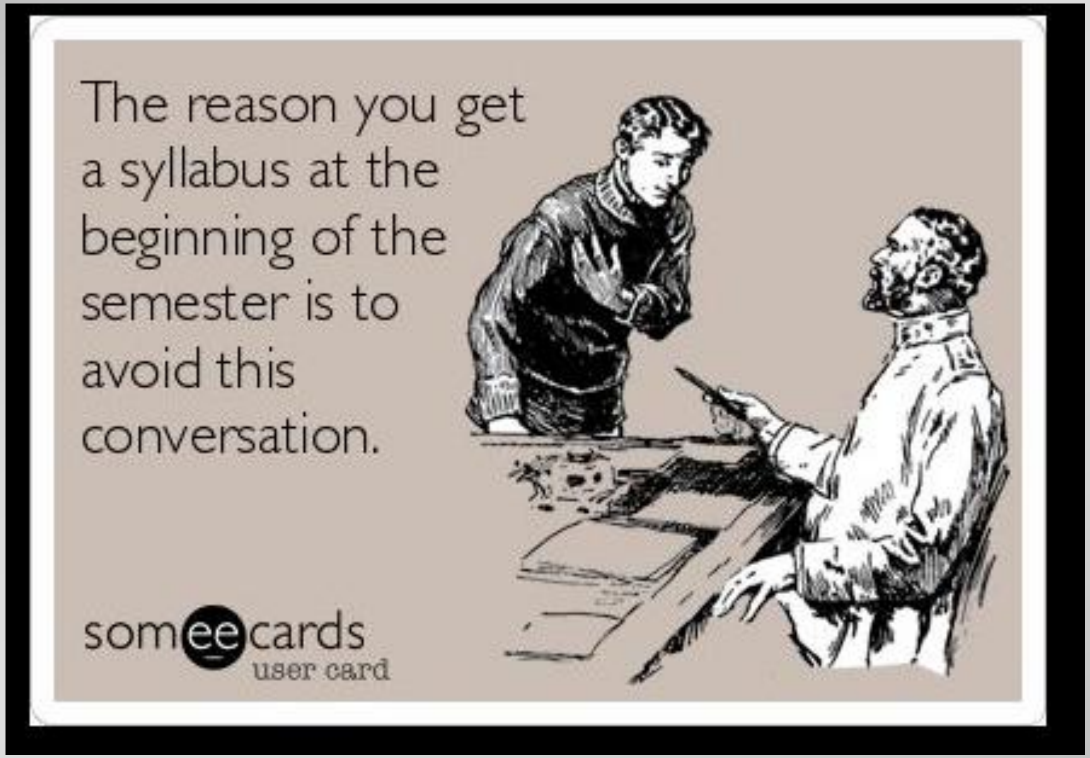


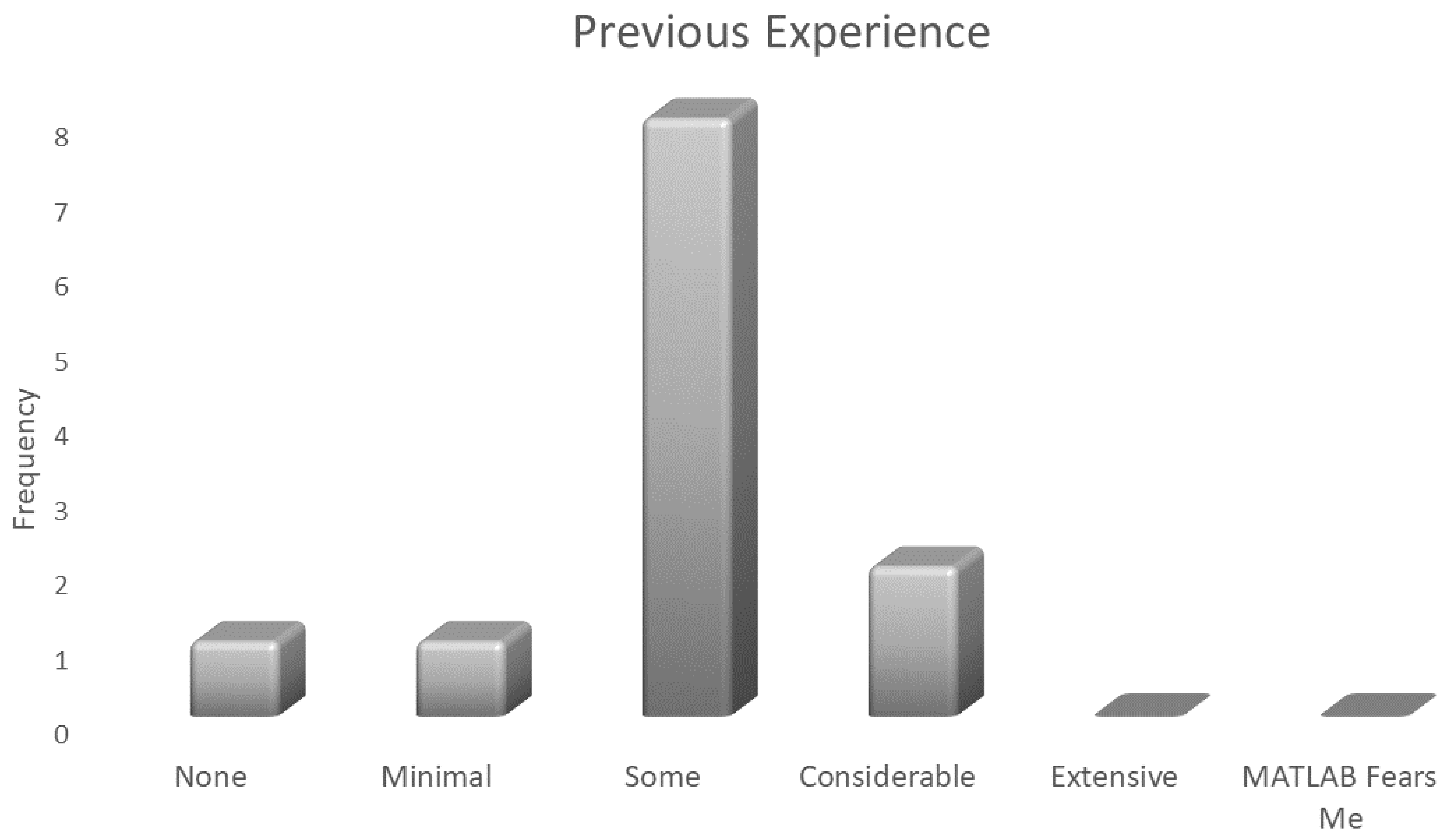


But first…

SYLLABUS AND WEBSITE

Roadmap

- Classic (Time or Frequency) vs. Newer (Time-Frequency) Approaches
  - Time Approaches
  - Frequency Approaches
  - Time-Frequency Approaches
- Brief discussion of Neural Sources and interpretation
- Guidelines for writing good code
- Code workshop part 1!


Previous Experience
Frequency
0
1
2
3
4
5
6
7
8
None
Minimal
Some
Considerable
Extensive
MATLAB Fears Me

Expectations

- Learn more about analyzing neuroimaging data.
- I've taken two undergraduate MATLAB courses with Dr. Higgins and hope to build on that small (and rusty) foundation in this course to learn how to intelligently develop scripts that support strong neural data analyses. I'd love to gain enough knowledge, understanding, and experience to hatch a stronger data analysis plan for the research proposal I developed in another class.
- I'd like to get a deeper understanding of MATLAB and of analytic techniques that work on multivariate longitudinal data.

Expectations

- Some skills to analyze.
- Building my skills in analyzing neural data in MATLAB and learning new techniques I could apply to my research. I have a bit of experience in MATLAB, but my background is primarily in python. I have worked on some projects involving neural data analysis but I still feel that I am somewhat of a beginner and would like to gain a deeper understanding since my research (single-unit and ensemble recording in rodents) involves a lot of this type of work.

Expectations

- I plan to develop my skills in using MATLAB beyond the little bits I have learned from being an RA. So far, I have only used Matlab to sort through slices of MRI and fMRI images so I am excited to learn new applications of the software.
- I don't know much about time frequency analysis, so hopefully learn more about that.
- Learn analysis skills to apply to my own research.

Expectations

- Broadening and strengthening my neural time series coding ability and conceptualization of EEG related measures. Also establishing a pipeline and generation foundation for neural-cardiac coupling
- That I become proficient in MATLAB, adequately learn Mathematical theory as outlined in the calendar, and subsequently apply what I've learned to process actual datasets.
- I'm hoping to establish basics and foundations of coding in MATlab that I can build upon to use for research.

Expectations

- Brushing up on my MATLAB knowledge and getting familiar with using it for EEG preprocessing and analysis, so I can collaborate on EEG research in my lab (I'm the only one who is familiar with MNE, unfortunately).

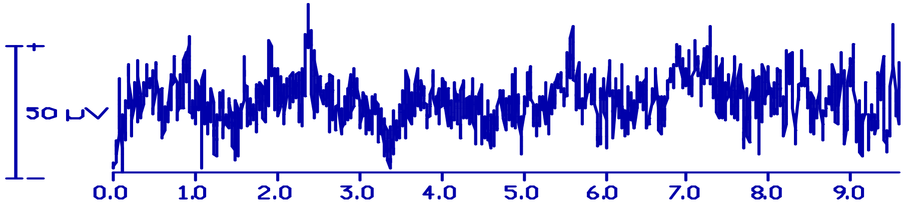
Time Approaches: ERPs (Event-related Potentials)

- What/how
- Advantages
- Disadvantages

Overview

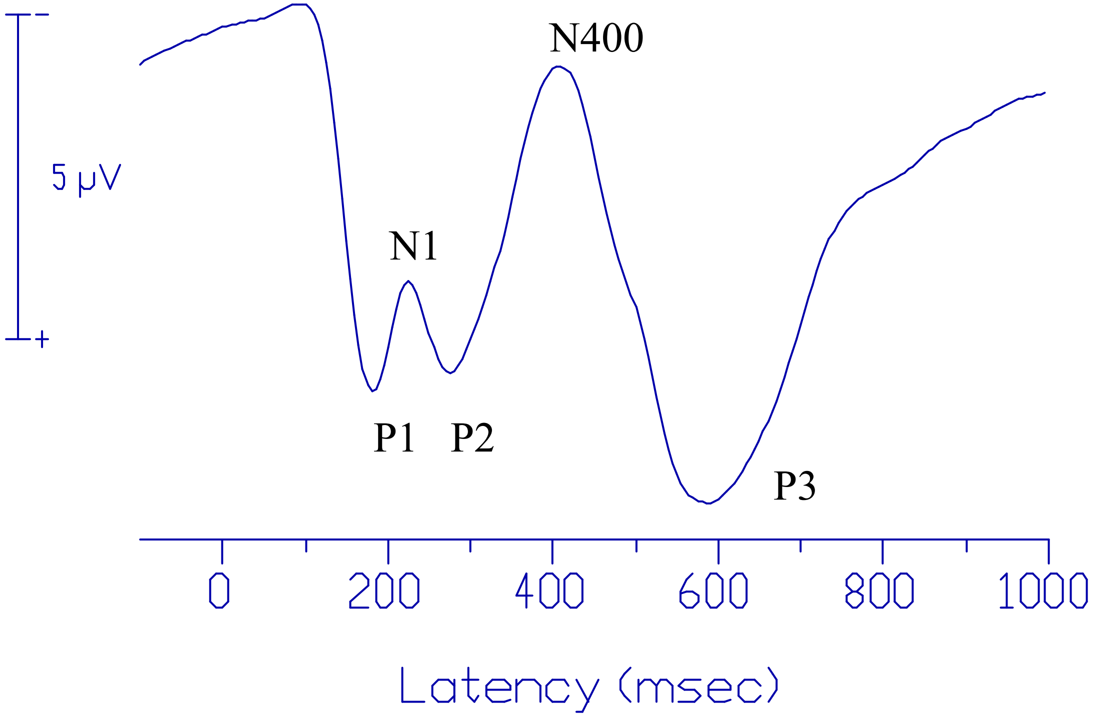
Event-related potentials are patterned voltage changes embedded in the ongoing EEG that reflect a process in response to a particular event: e.g., a visual or auditory stimulus, a response, an internal event

Ongoing EEG



Stimuli

Visual Event-related Potential (ERP)



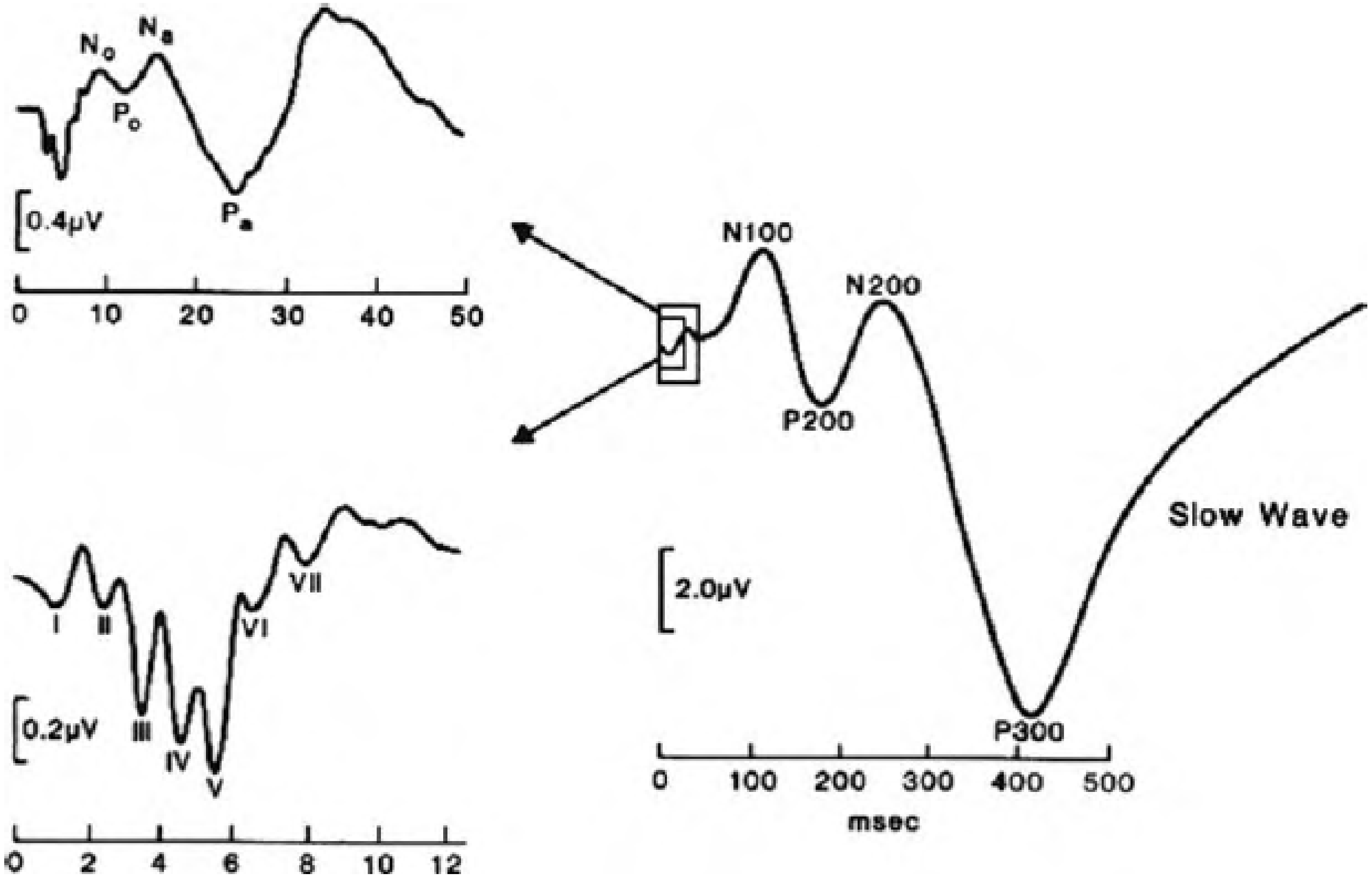
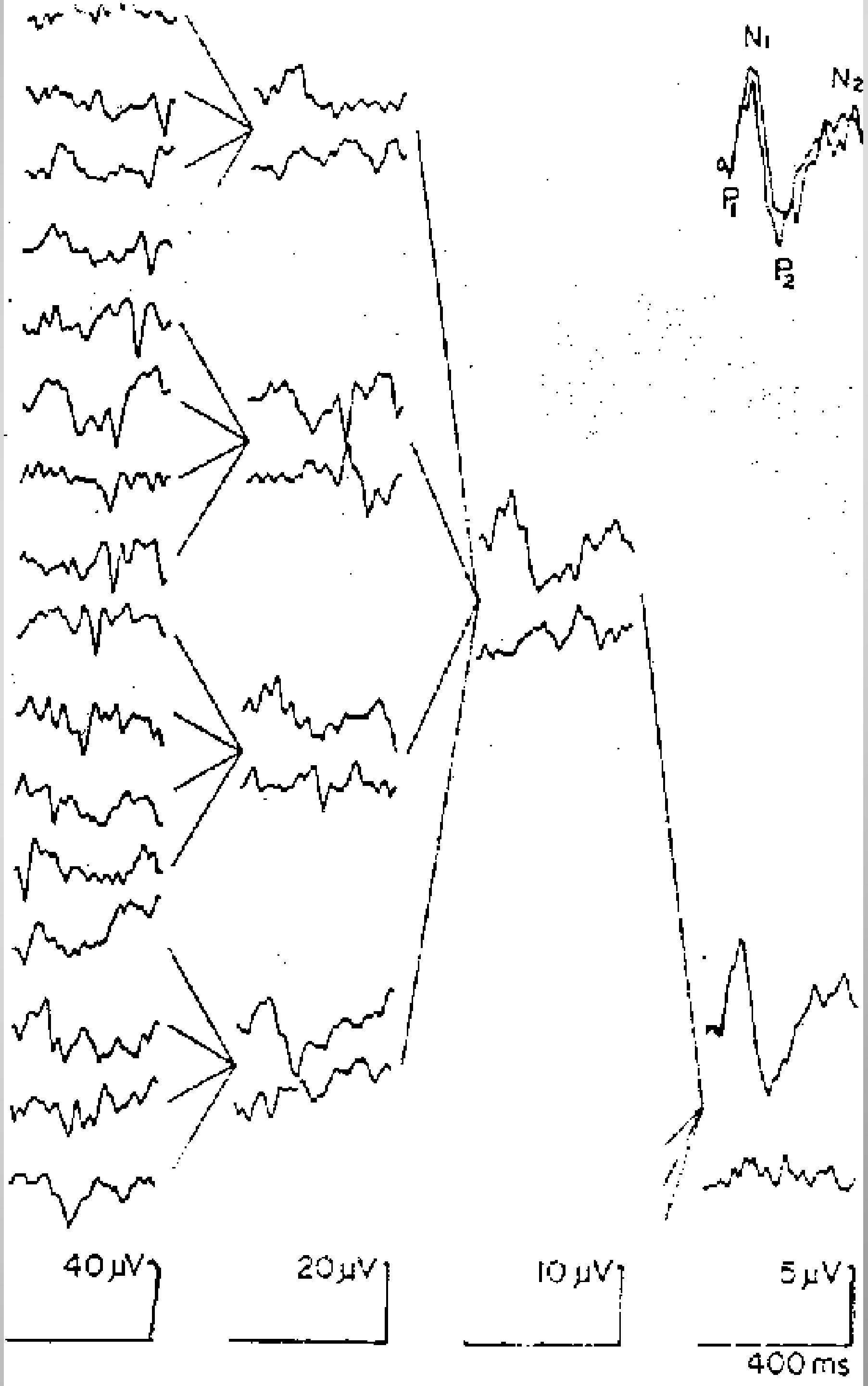


Figure 4.2. A schematic representation of ERP components elicited by auditory, infrequent target stimuli. The three panels represent three different voltage × time functions: the left bottom panel shows the very early sensory components (with a latency of less than 10 ms); the left top panel shows the middle latency sensory components (with a latency of between 10 and 50 ms); and the right panel shows late components (latency exceeding 50 ms). Note the different voltage and time scales used in the three panels, as well as the different nomenclatures used to label the peaks (components). (Adapted with permission of the author from Donchin, 1979, with kind permission of Springer Science and Business media.)

Time-locked activity and extraction by averaging



Matlab Demo!

- Plus-Minus averaging to show impact of noise:
  - PlusMinus.m

Welcome to the MATLAB Environment!

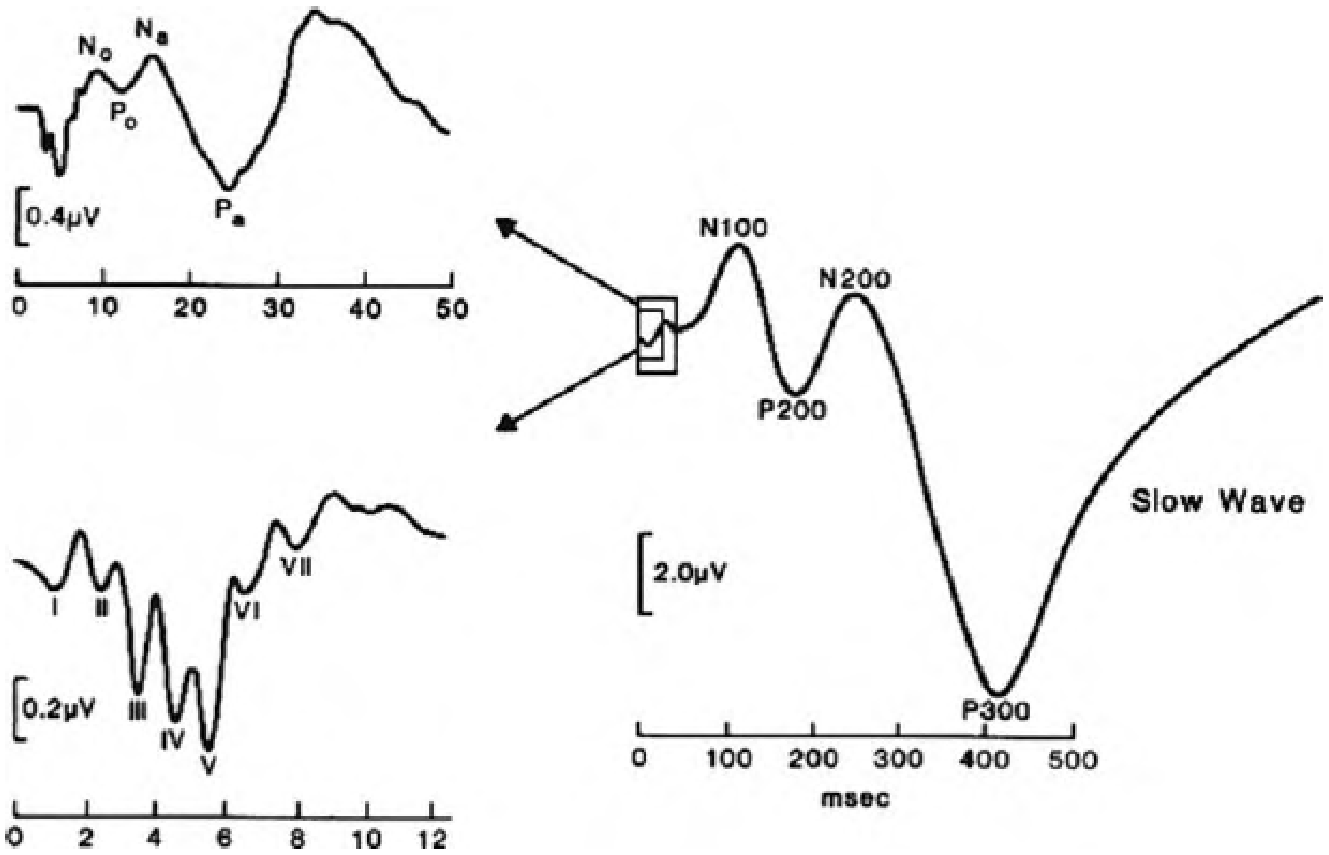
The Classic View:
Time-locked activity and extraction by signal averaging

- Ongoing activity reflects "**noise**"
- Activity that reflects processing of a given stimulus "**signal**"
- The signal-related activity can be extracted because it is **time-locked** to the presentation of the stimulus
- Signal Averaging is most common method of extracting the signal
  - Sample EEG for ~1 second after each stimulus presentation & average together across like stimuli
  - Time-locked signal emerges; noise averages to zero
  - Signal to noise ratio increases as a function of the **square root** of the number of trials in the average

What does the ERP reflect?

- May reflect sensory, motor, **and/or** cognitive events in the brain
- Reflect the synchronous and phase-locked activities of large neuronal populations engaged in information processing

Component is a "bump" or "trough"



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Making Meaning from the bumps

Pores o'er the Cranial map with learned eyes,
Each rising hill and bumpy knoll decries
Here secret fires, and there deep mines of sense
His touch detects beneath each prominence.

Time Approaches: ERPs

- What/how
- Advantages
- Disadvantages

ERPs Advantages

- Simple, easy to derive
- Exquisite temporal resolution
  - Time-frequency approaches will blur temporal precision
  - Although … time precision seldom realized with ERPs
- Extensive literature spanning decades
- Because of ease to compute, can provide check on single-subject data

ERPs Disdvantages

- ERPs blind to non-phase-locked activity

ERPs can be “blind” to activity

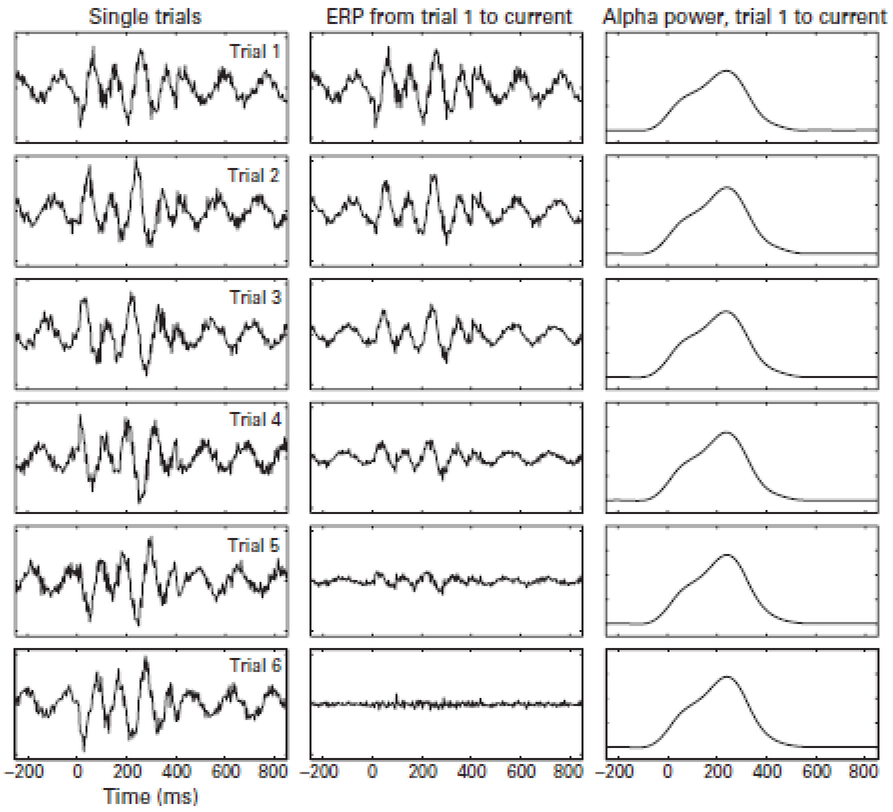


Figure 2.1
Simulated data showing how time-locked but not phase-locked activity (left column) is lost in ERP averaging (middle column) but is visible in band-specific power (right column). Each row in the left column shows a different trial, and each row in the middle and right columns shows averages from the first until the current trial.

Cohen, 2014

ERPs Disdvantages

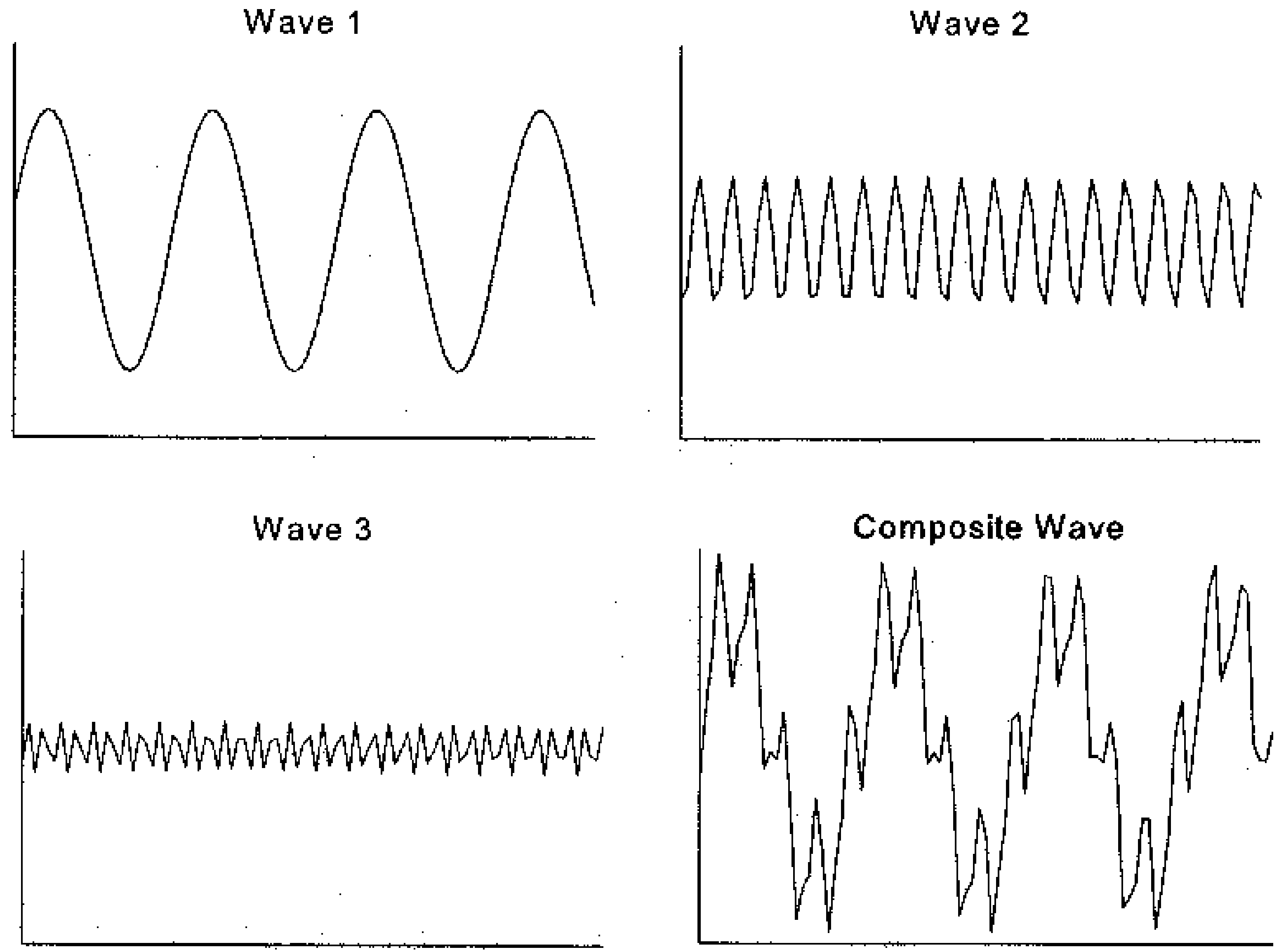
- ERPs blind to non-phase-locked activity
- Limited basis for linking to physiological mechanisms
  - Time-frequency approaches assess oscillations
  - Neurophysiological mechanisms that produce ERPs are less well understood than the neurophysiological mechanisms that produce oscillations.

Frequency Approaches: FFT etc

- What/how
- Advantages
- Disadvantages

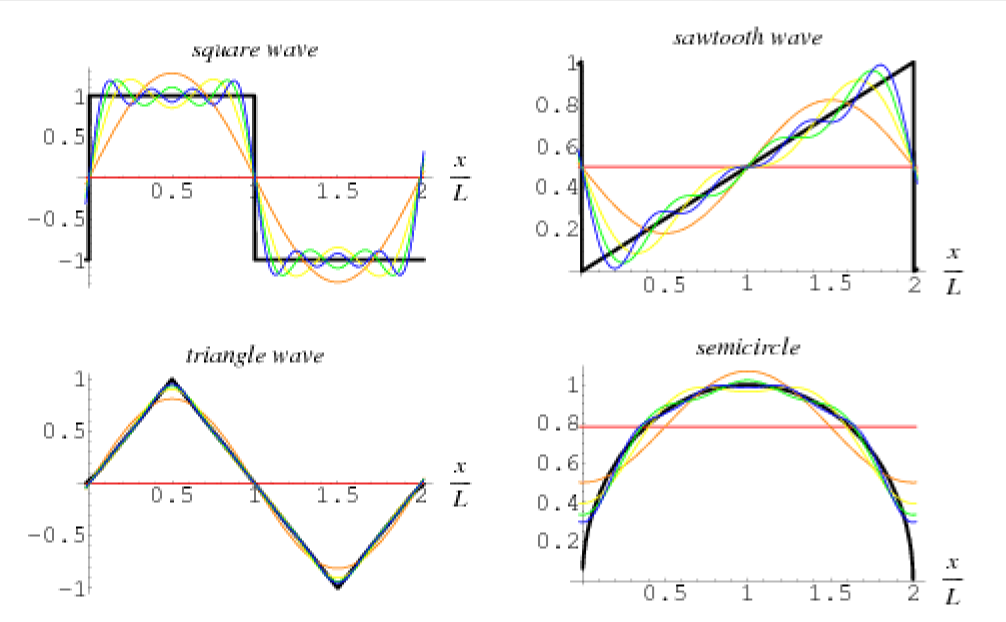
Frequency Domain Analysis

- 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

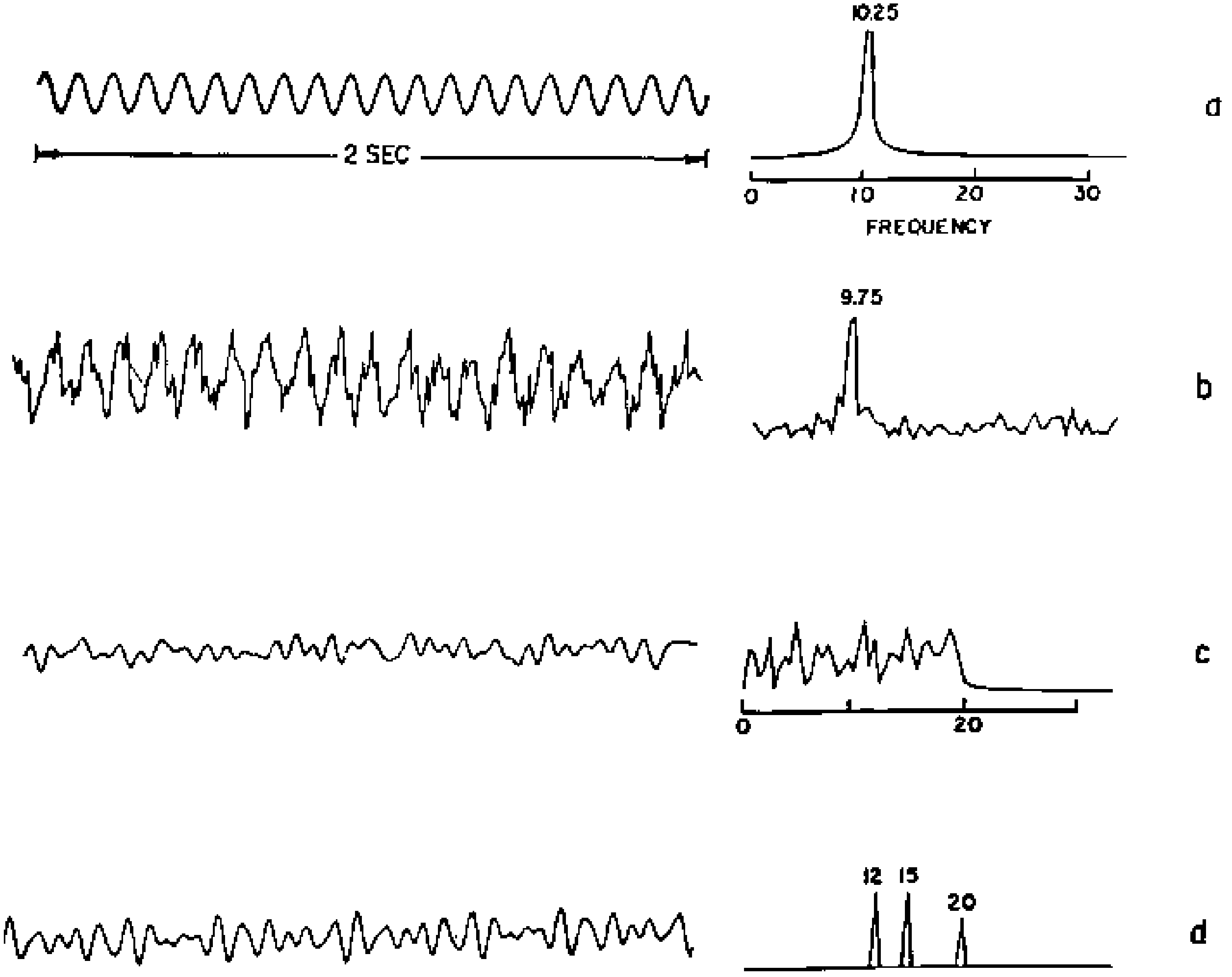


Interactive Fourier!

- Web Applet
- www.falstad.com/fourier/

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.

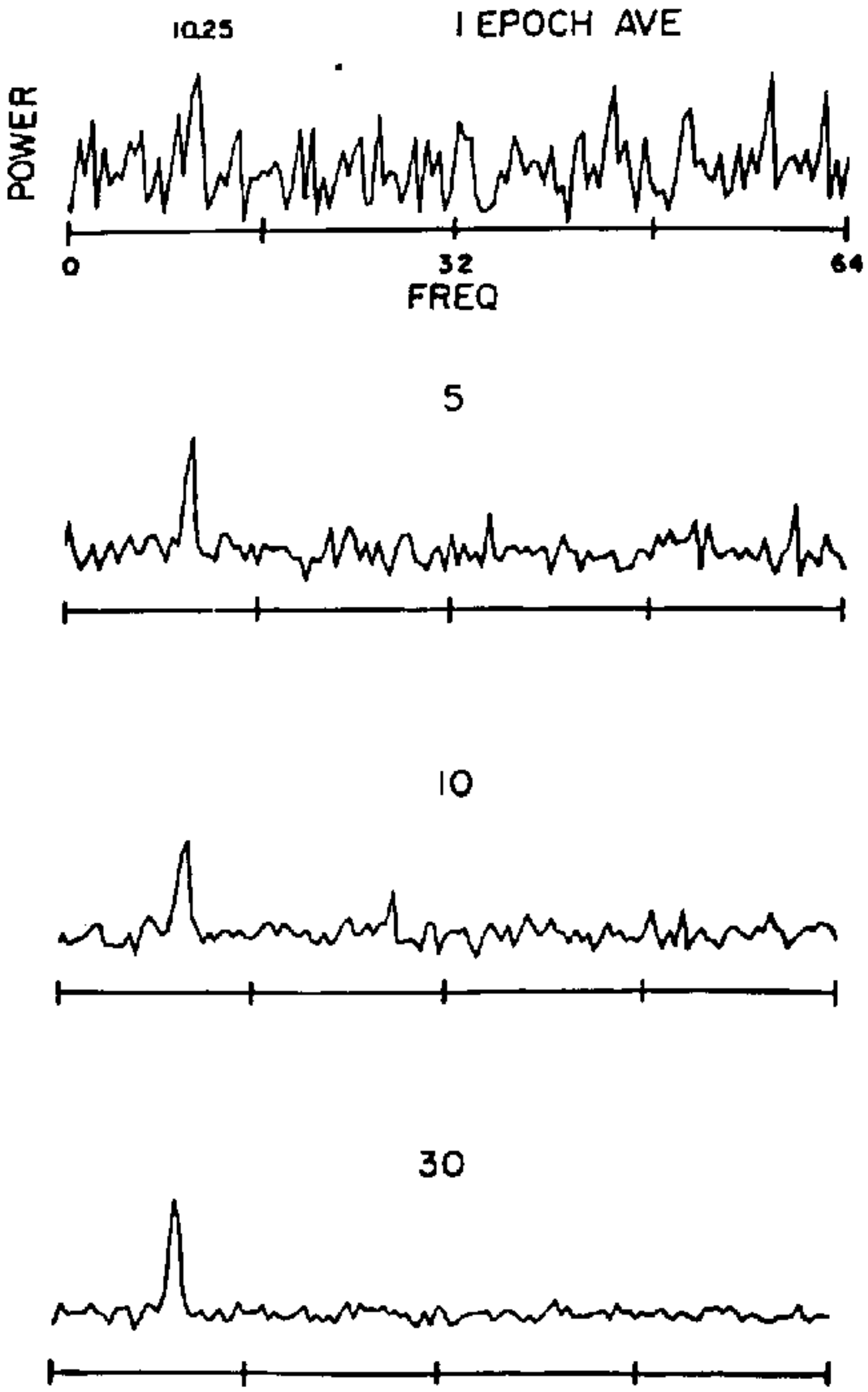


Time Domain

Frequency Domain

Averaging Multiple Epochs improves ability to resolve signal

Note noise is twice amplitude of the signal



Matlab Demo!

- Advanced Coding Challenge:
  - Find two snippets of the same song with different frequency characteristics
  - Use Audacity to create two wav files
  - Alter m code to plot spectra of these two snippets

Frequency Approaches: FFT etc

- What/how
- Advantages
- Disadvantages

Advantages of Frequency Approaches

- Sensitive to all frequencies below Nyquist
- Sensitive to phase-locked and non-phase-locked signals

NYQUIST?

Small detour to discuss the nature of digital versus analog signals

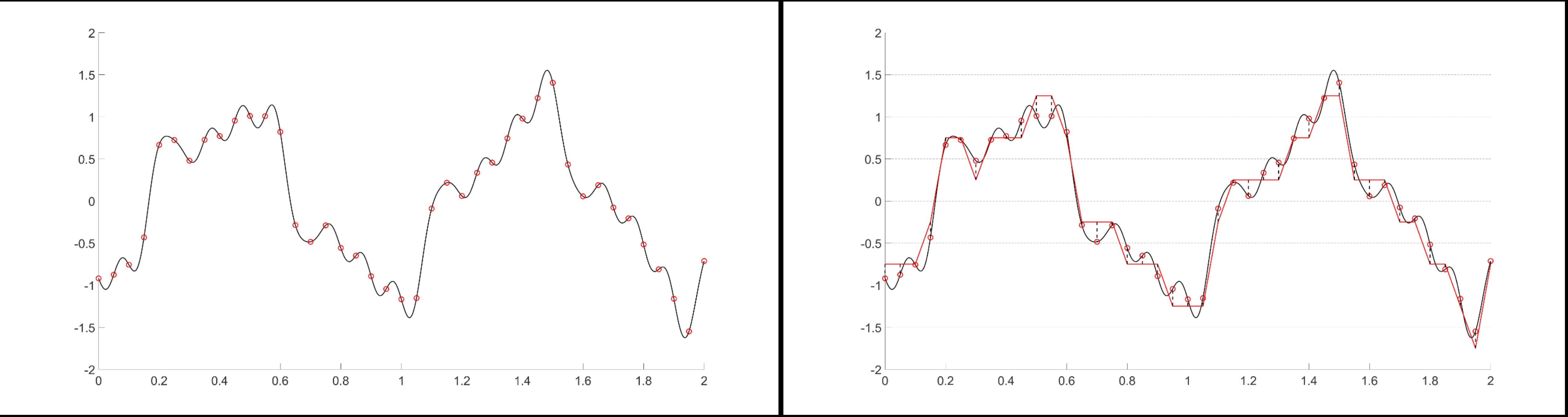


Figure 5: A signal sampled at 20 Hz. Discrete-time sampling (left panel) allows for continuous y-axis (μV) values, whereas digitally-sampled signals (right panel) must use a limited number of y-axis values. The three-bit converter illustrated here (right panel) allows for $2^3=8$ distinct values, providing only a course approximation of the signal voltage. The right panel depicts the discrete sample value (red circle) and the 3-bit digital equivalent (red line), and the discrepancy (dashed vertical black lines).

From: Curham & Allen (2022)

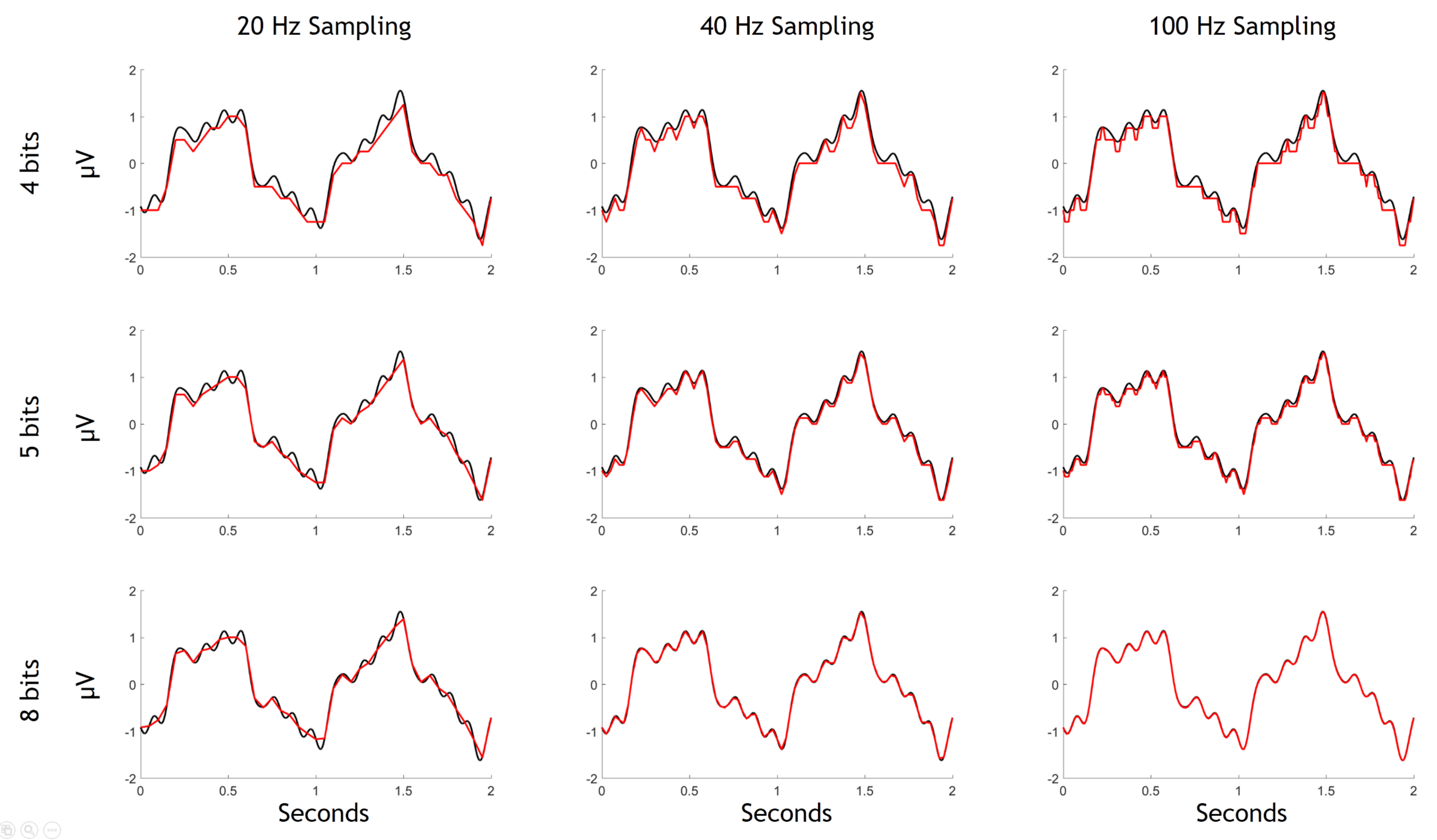


Figure 6: A comparison of a signal (black line) sampled (red line) at three sampling rates (20, 40, 100 Hz) and using three different converter resolutions (4-bit, 5-bit, and 8-bit) that allow for 16, 32, and 128 distinct μV values. Low bit-resolution was used here for illustrative purposes; commercial converters are typically 12-bit (4096 values) or 16-bit (65536 values).

From: Curham & Allen (2022)

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

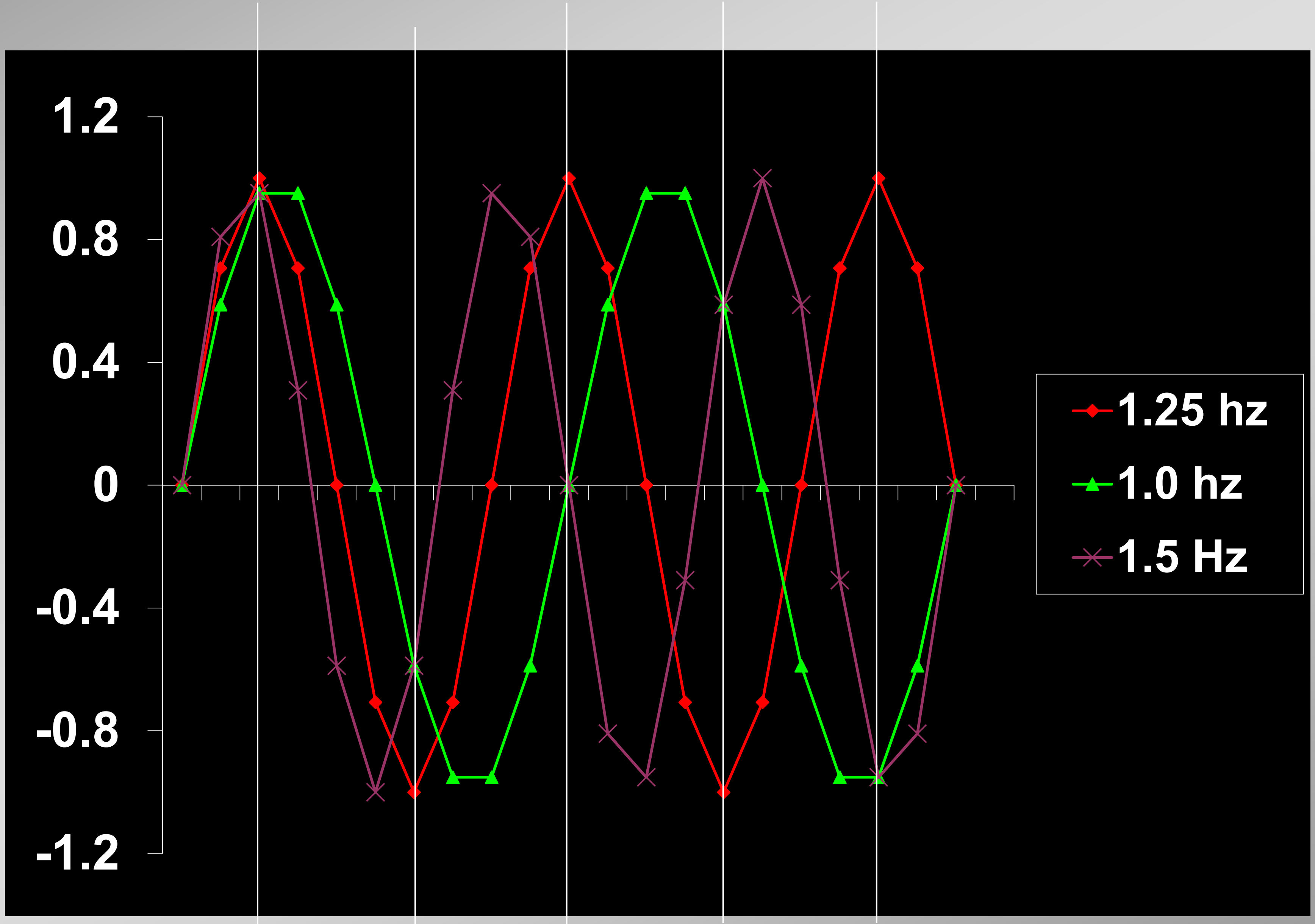
Harry Nyquist

The Problem of Aliasing

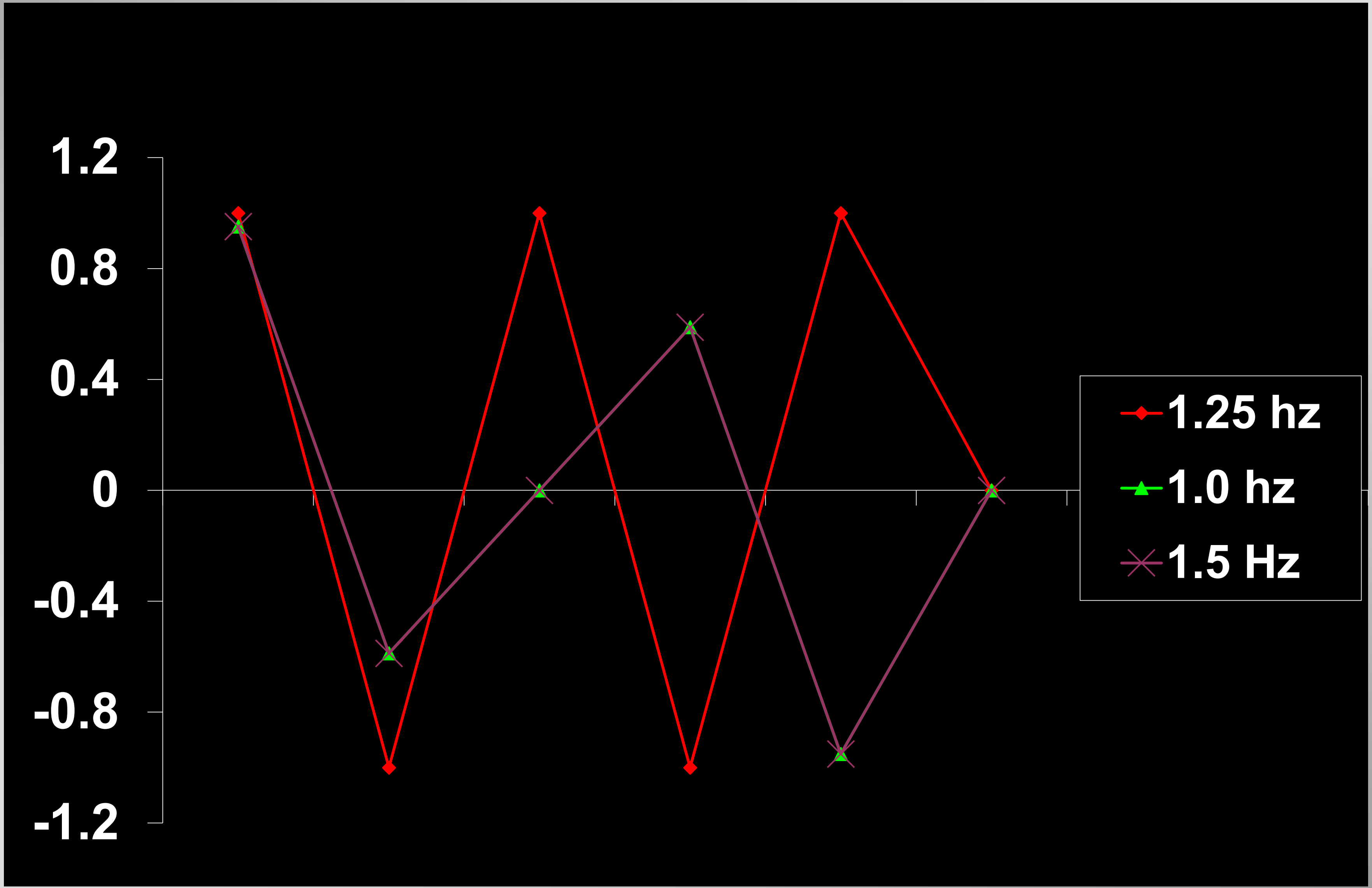
- Comments
  - Wave itself looks distorted, but frequency is captured adequately.
  - Frequencies faster than the Nyquist frequency will not be adequately represented
  - Freq of
    Nyquist + X Hz
    appears as
    Nyquist - X Hz
  - Minimum sampling rate required for a given frequency signal is known as Nyquist sampling rate

Harry Nyquist

Aliasing Demo (Part 1, 10 Hz Sampling Rate)



Aliasing Demo (Part 2, 2.5 Hz Sampling Rate)



Matlab Demo of Aliasing

Solutions to Aliasing

- Sample very fast
- Use anti-aliasing filters to keep signals below **Nyquist Frequency**
- KNOW YOUR SIGNAL!

Advantages of Frequency Approaches

- Sensitive to all frequencies below Nyquist
- Sensitive to phase-locked and non-phase-locked signals

Frequency Approaches: FFT etc

- What/how
- Advantages
- Disadvantages

DisAdvantages of Frequency Approaches

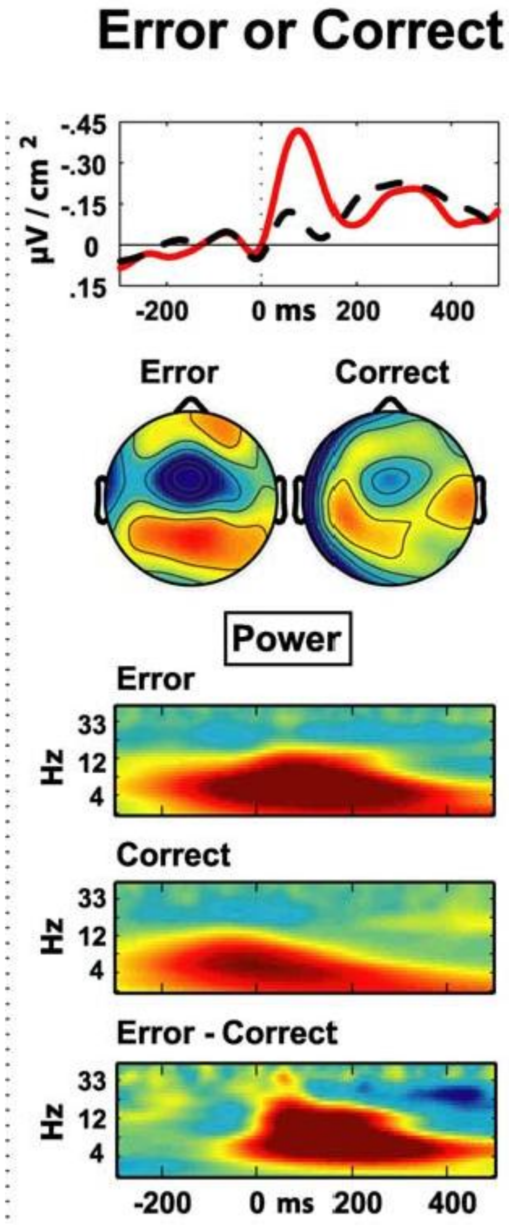
- Temporally nonspecific
- Power interpretation is ambiguous:
  - More is more?
  - More is more often?

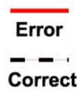
Time-Frequency Approaches

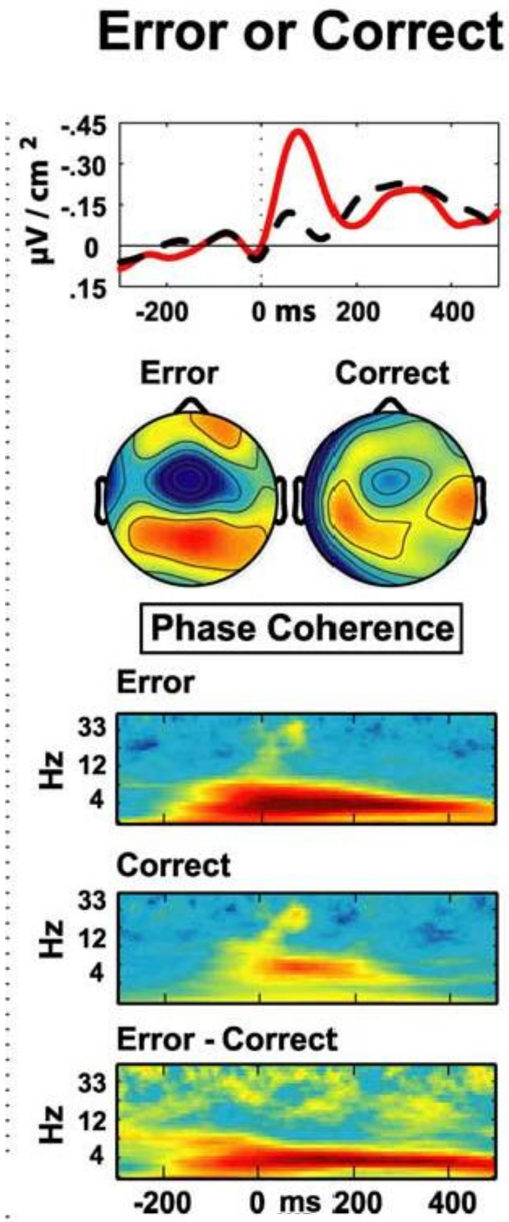
- What/how
- Advantages
- Disadvantages

Time-Frequency Representation:

Power

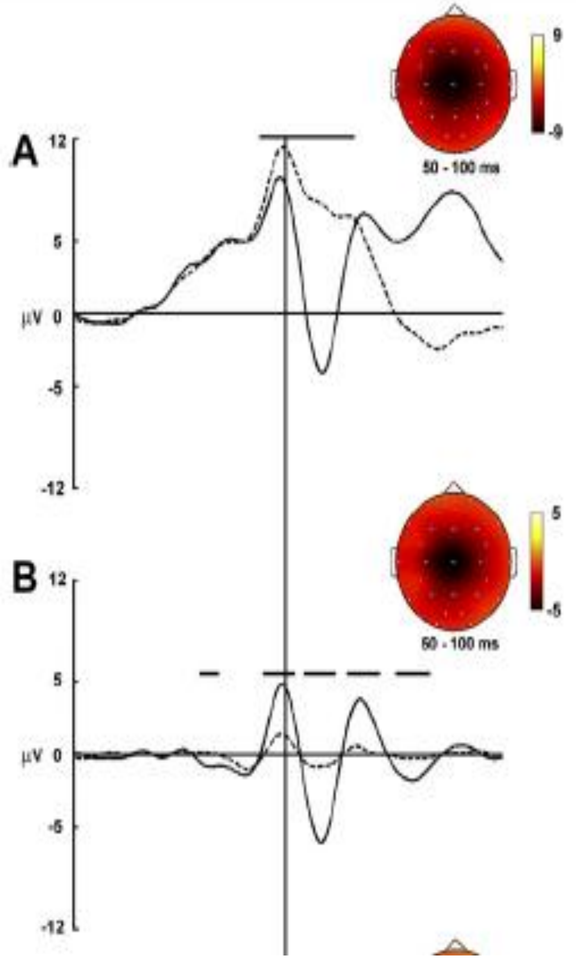


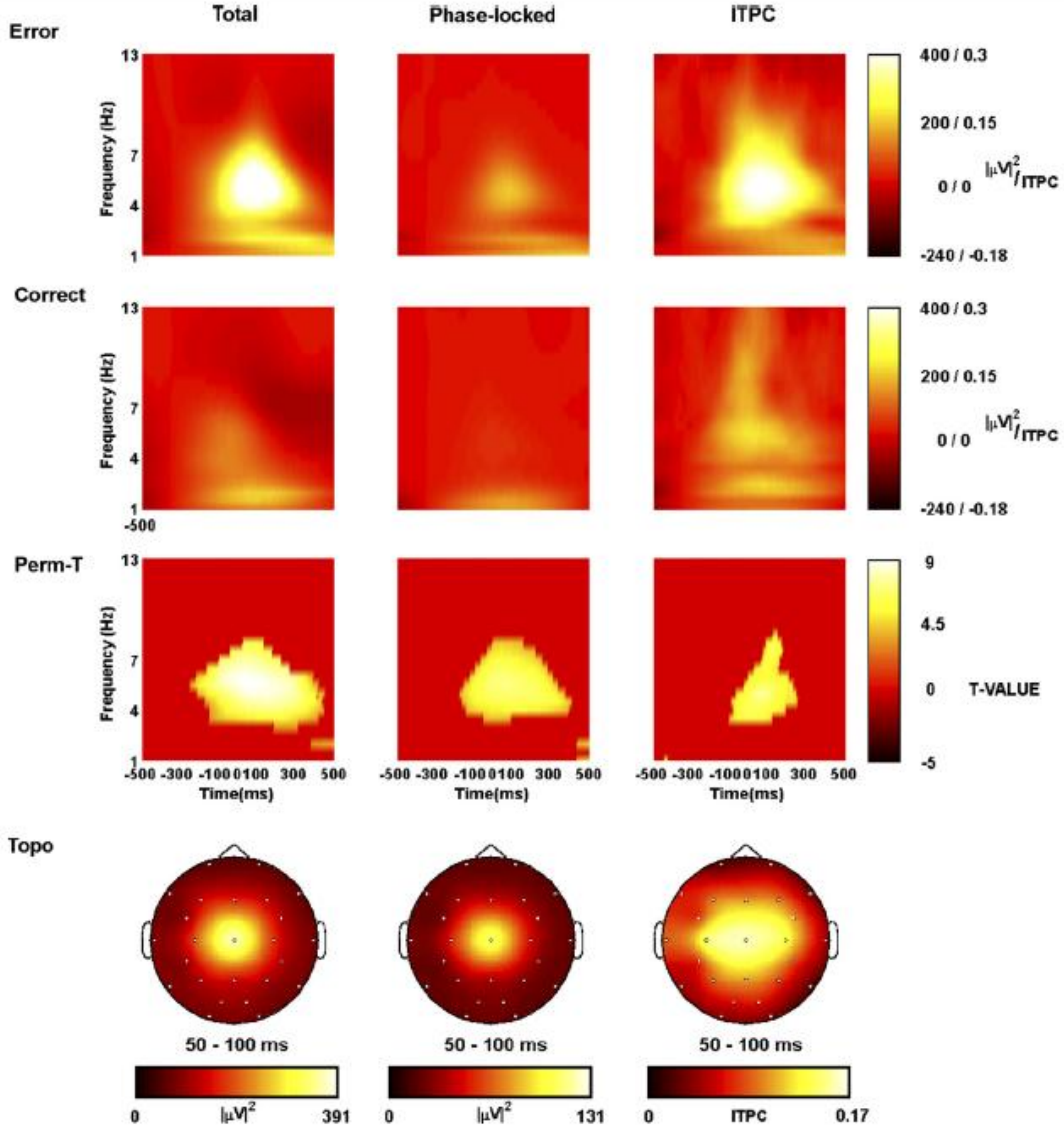




Phase

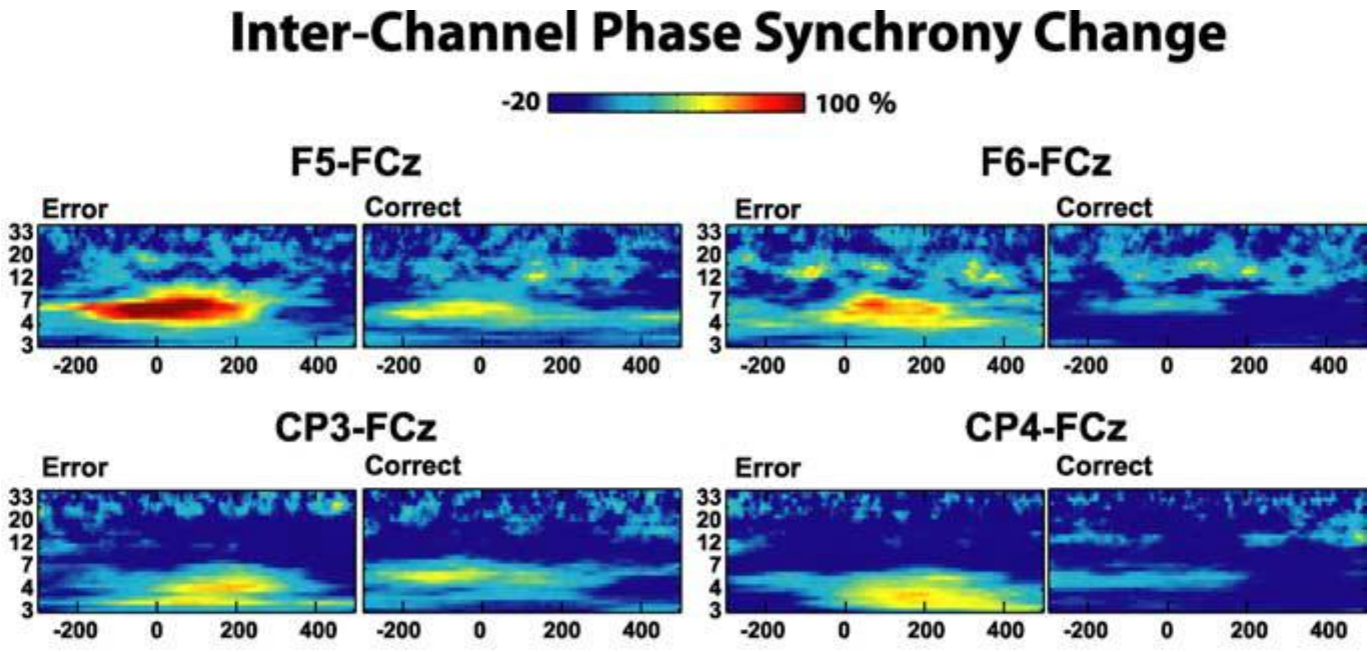
Cavanagh, Cohen, & Allen, 2009





Trujillo & Allen, 2007

Time-Frequency Representation: Power



Cavanagh, Cohen, & Allen, 2009

Time-Frequency Approaches

- What/how
- Advantages
- Disadvantages

Time-Frequency Advantages

- Results can be interpreted in terms of neurophysiological mechanisms of neural oscillations.
  - Oscillations are a fundamental neural mechanism that supports aspects of synaptic, cellular, and systems-level brain function across multiple spatial and temporal scales (Cohen, 2014)
- Oscillations studied across multiple species and levels of analysis (single cell, LFP, intra-cranial, scalp)
- Captures more of brain dynamics than ERPs

Power increase in the absence of any phase locking

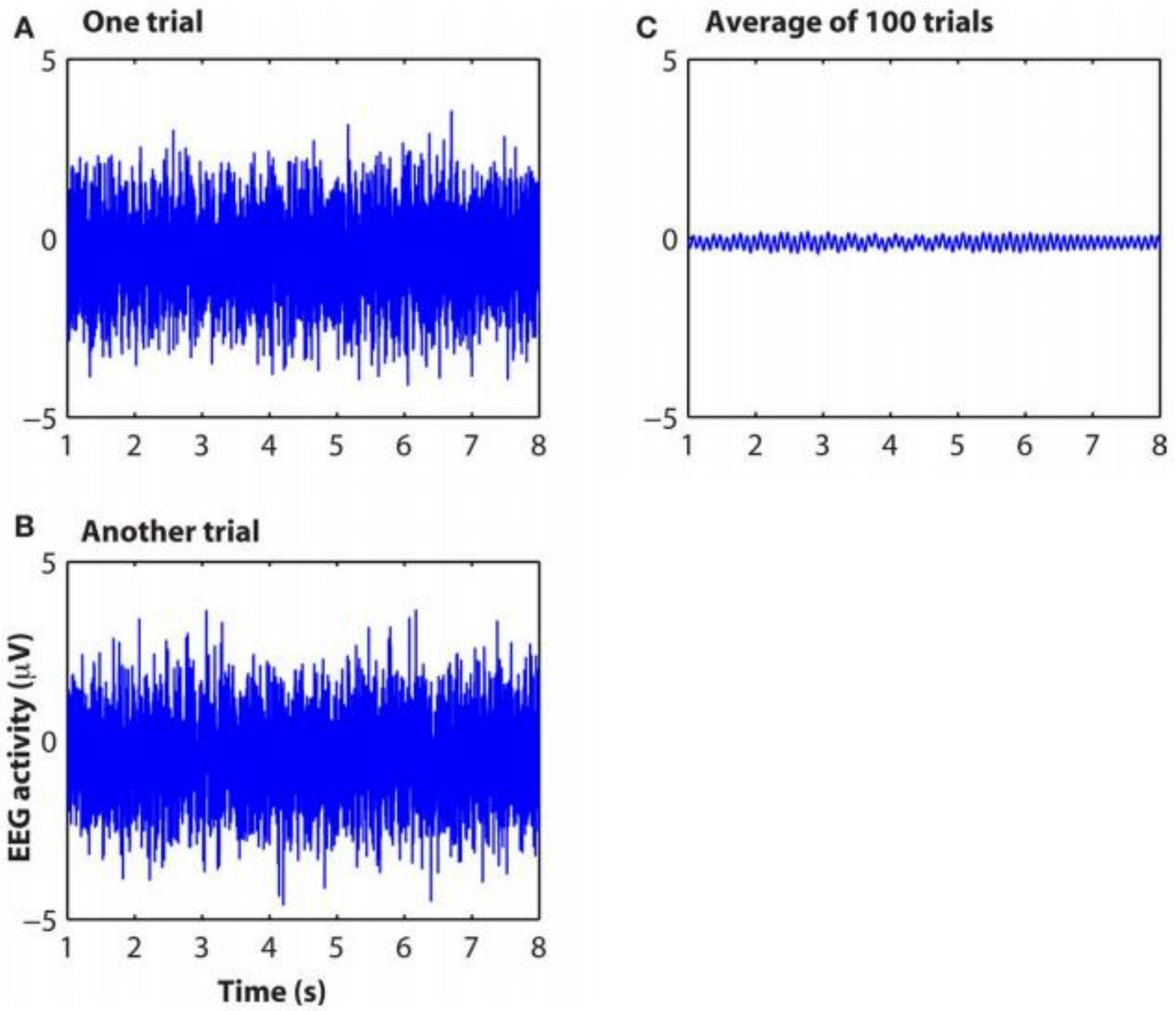


FIGURE 3 | Simulated data showing how information contained in raw EEG data [**(A,B)**: single "trials"] is not apparent in the event-related potential **(C)** but is readily observable in the time–frequency representation **(D)**. Matlab code to run this simulation is available from the author.

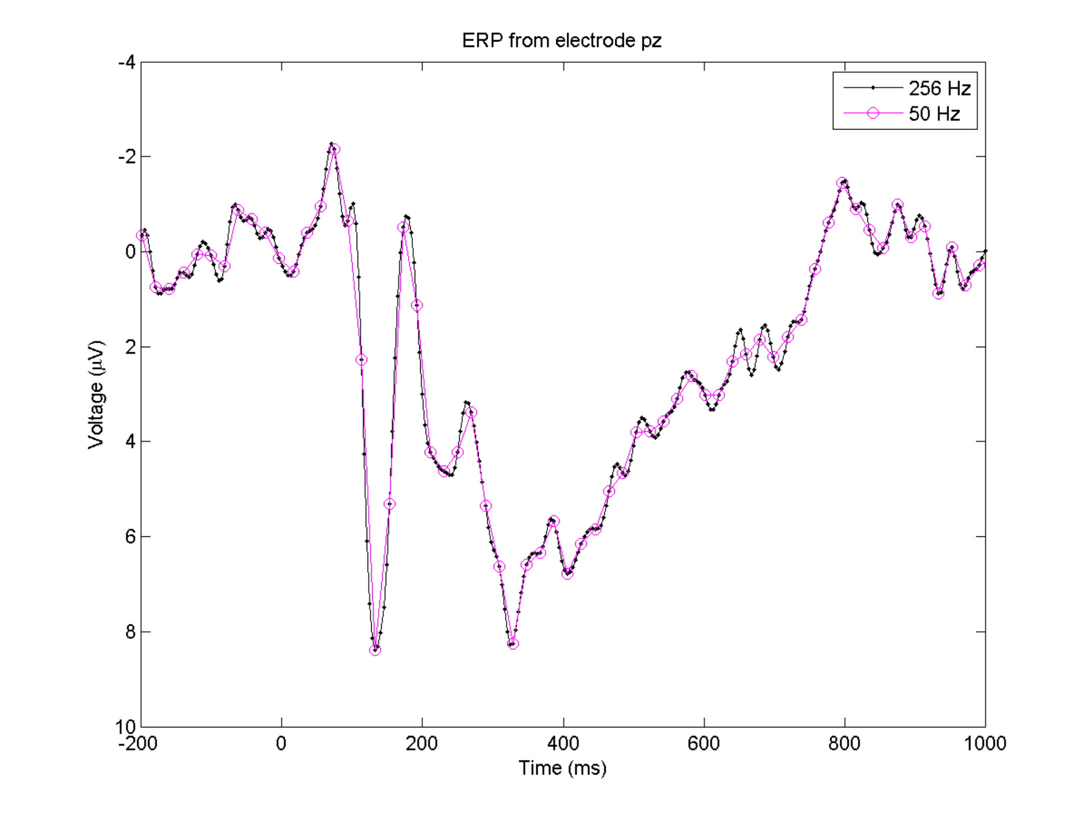
Cohen, 2011, *Frontiers in Human Neuroscience*

Time-Frequency Approaches

- What/how
- Advantages
- Disadvantages

Time-Frequency Disadvantages

- Decreased temporal precision vs ERPs
  - Must observe a full oscillation to capture it
  - Greater loss of temporal precision at lower frequencies
  - BUT NOTE (Time-frequency proponents take heart!)

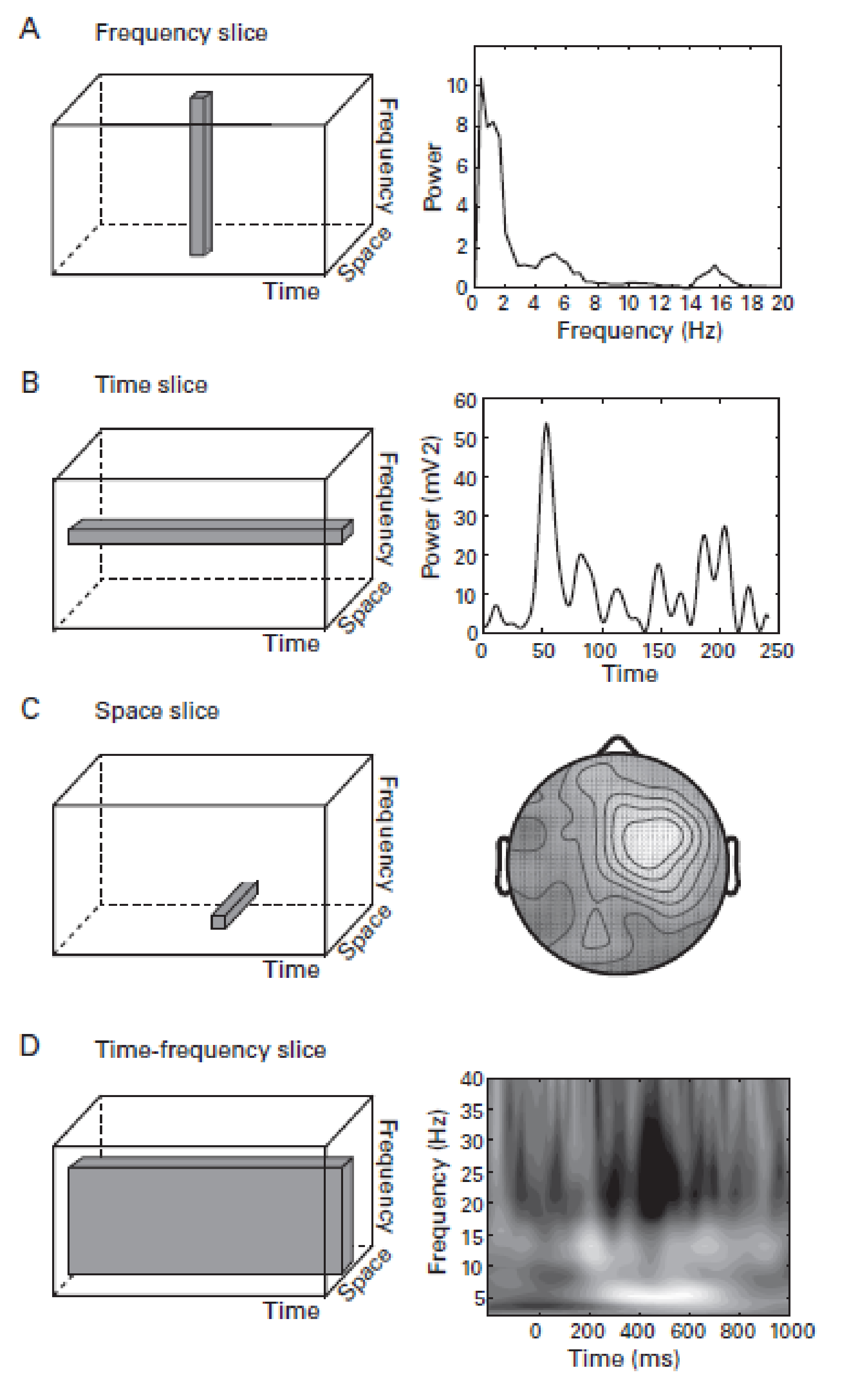


Cohen, 2014

Time-Frequency Disadvantages

- Decreased temporal precision vs ERPs
  - Must observe a full oscillation to capture it
  - Greater loss of temporal precision at lower frequencies
  - BUT NOTE (Time-frequency proponents take heart!)
- Diverse range of analysis possibilities leads combinatorial explosion of possible ways to screw up!
  - Running analyses improperly
  - Running improper analyses
  - Rendering inappropriate interpretations
  - Multiple comparisons problem
    - Time-frequency space is large
    - Multiplied by many electrodes!
  - The “paralysis of analysis” (Cohen, 2014)
- TF approaches in EEG researcj are *relatively* new, but growth in use is exponential!

How to view Time-Frequency Results



Cohen, 2014

How to view Time-Frequency Results

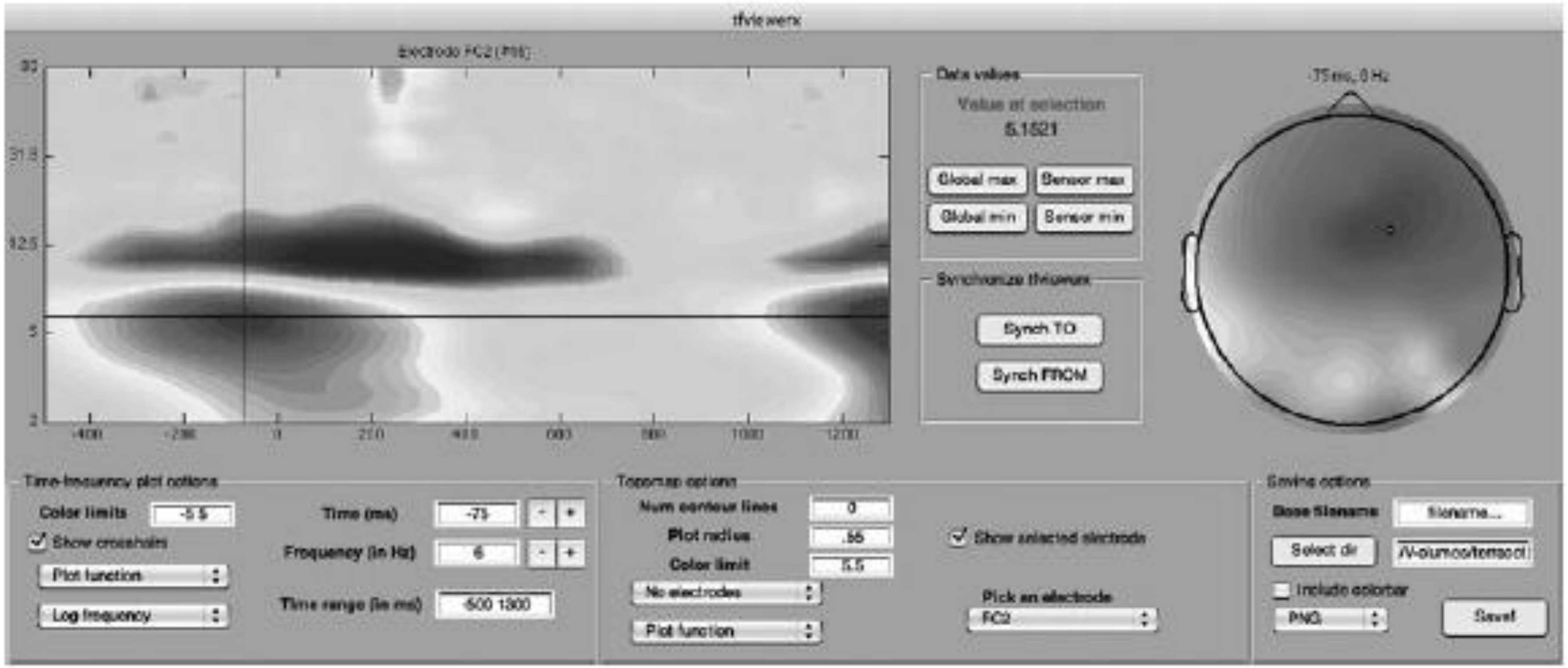


Figure 3.4

A screen-shot of the data-cube-viewing utility tfviewerx, which is available online with the Matlab code. Mouse clicks on the time-frequency plot update the topographical map to show the scalp distribution at that time-frequency point, and mouse clicks on the topographical map update the time-frequency plot to show the time-frequency dynamics at the nearest electrode. Multiple tfviewerx windows can be opened (e.g., to view results from different conditions) and can be synchronized to show the same time-frequency-electrode point across plots. Type "help tfviewerx" in Matlab to learn about how to use this utility.

Cohen, 2014

Matlab Demo!

- tfviewerx

- A Non-coding Challenge:
  - Explore the time-frequency-topography space using the preloaded data in tfviewerx

Be suspect: Time-Frequency Results

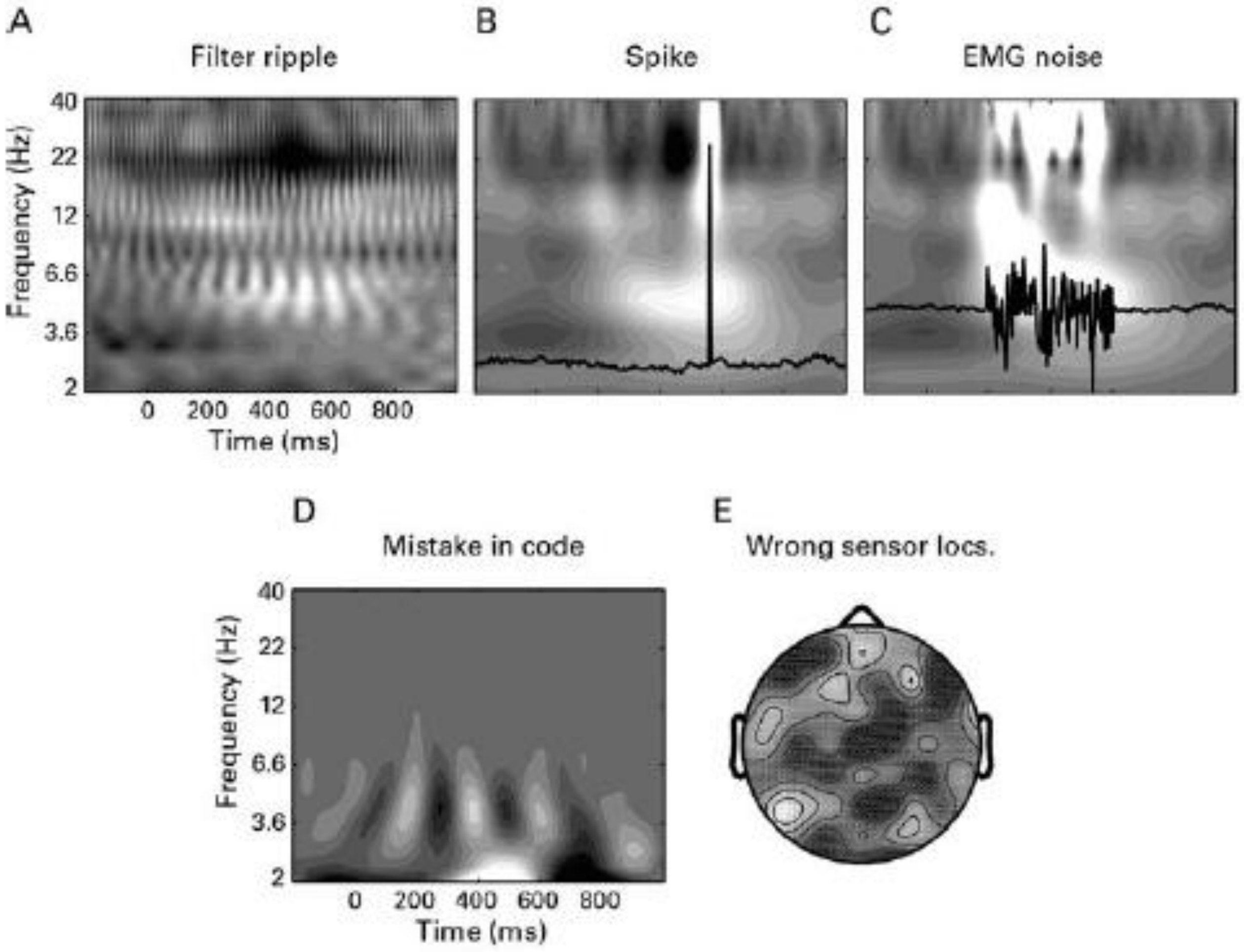


Figure 3.5
Some features of time-frequency results that should arouse suspicion, although they are not necessarily artifacts. In panels B and C, the offending single trial (out of 99 otherwise good-data trials) is superimposed on the time-frequency plot (EEG trace amplitude is arbitrarily scaled). The topographical map in panel E was produced by randomly swapping electrode label-location mappings.

Cohen, 2014

Roadmap

- Classic (Time or Frequency) vs. Newer (Time-Frequency) Approaches
  - Time Approaches
  - Frequency Approaches
  - Time-Frequency Approaches
- **Brief discussion of Neural Sources and interpretation**
- Guidelines for writing good code
- Code workshop!

Brief comment on Neural Sources of EEG

- EEG blind to many signals
  - Insufficient number of neurons synchronously active
  - Electrical field geometry

Electrical Field Geometry

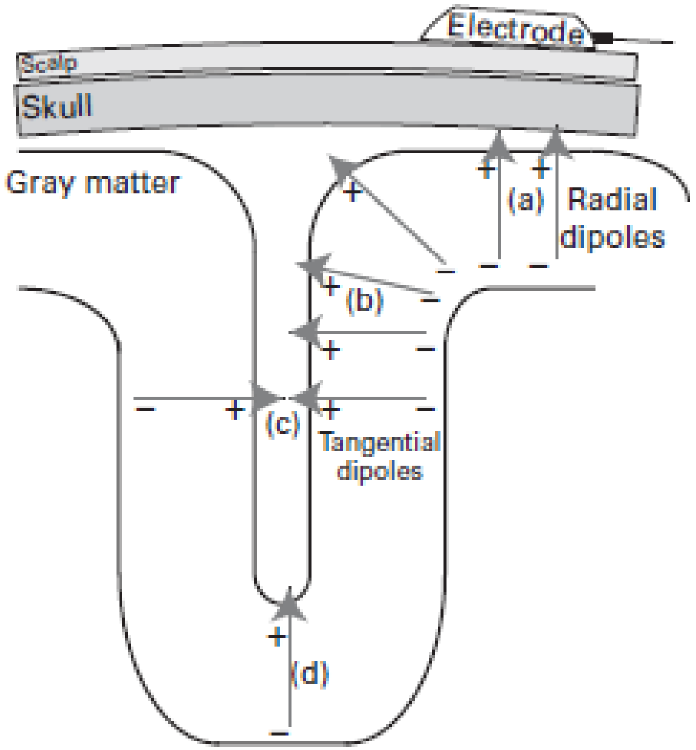


Figure 5.1
Illustration of dipoles in different orientations with respect to the skull. The dipoles illustrated in (a) will contribute the strongest signal to EEG, whereas the dipoles illustrated in (b) will contribute the strongest signal to MEG. The dipoles illustrated in (c) are unlikely to be measured because the dipoles on opposing sides of the sulcus produce electrical fields that are likely to cancel each other. The dipole illustrated in (d) will make a smaller contribution to EEG than dipole (a) because it is further away from the electrode. (This figure is inspired by figure 1 of Scherg 1990.)

Cohen, 2014

Brief comment on Neural Sources of EEG

- EEG blind to many signals
  - Insufficient number of neurons synchronously active
  - Electrical field geometry
  - Cortical Sources predominate for electrodes on the scalp (deep sources “buried”)
    - Field strength decreases exponentially from source

Brief comment an Causation

- EEG is only direct noninvasive measure of neural activity
- BUT… is the measured activity causal to the psychological process of interest?

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- **Guidelines for writing good code**
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Writing MATLAB Code

- Write Clean and Efficient Code
- Comment your code!
  - Suggestion: One comment per three lines of code
- Use Meaningful File and Variable Names
- Make Regular Backups of Your Code
  - Keep Original Copies of Modified Code
- Initialize Variables; pre-allocate matrices/cells
- Make functions!
- Test small segments and build outward
  - Use cells within code
- Read (and critique) other people's code

Roadmap

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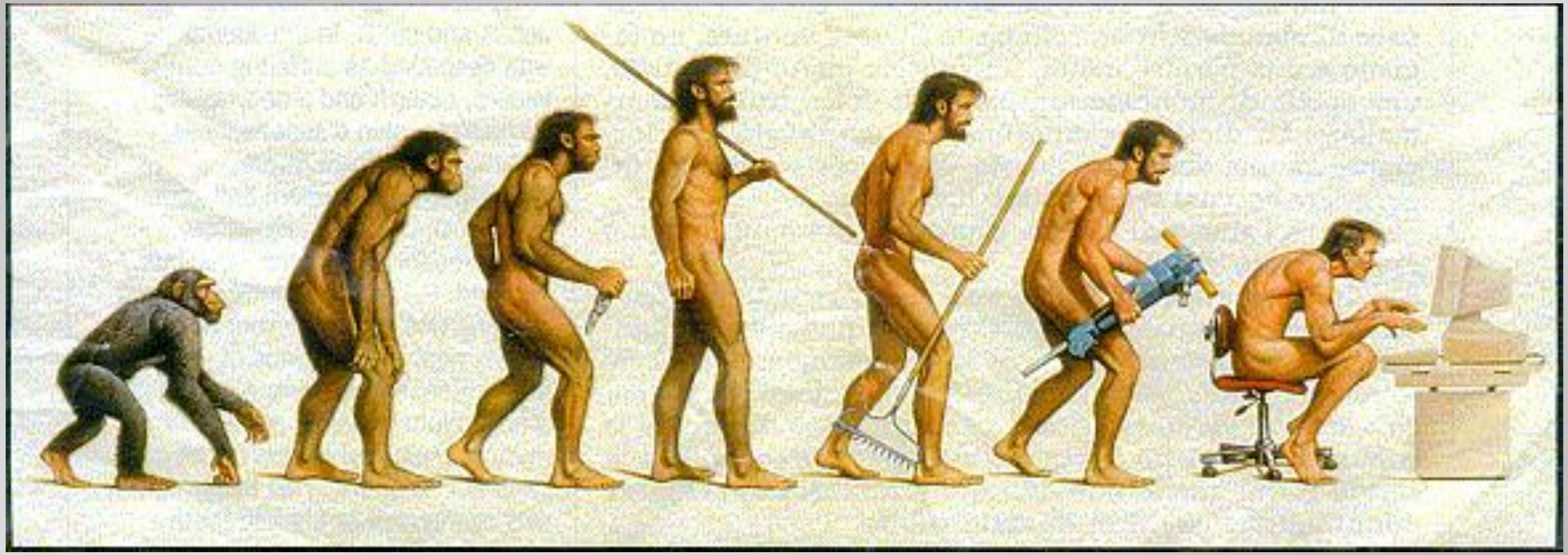
Let's Code!



What, we’re supposed to code already?!!!

- Fear not: Next week we’ll cover basics of MATLAB coding
- MATLAB “onramp” (2 hours and 15 minutes): https://matlabacademy.mathworks.com/details/matlab-onramp/gettingstarted