Frequency-domain EEG applications and methodological considerations

Announcements

- Papers: 1 or 2 paragraph prospectus due no later than Monday March 25
- 3x5s

A wee bit more on
Digital Signal Processing

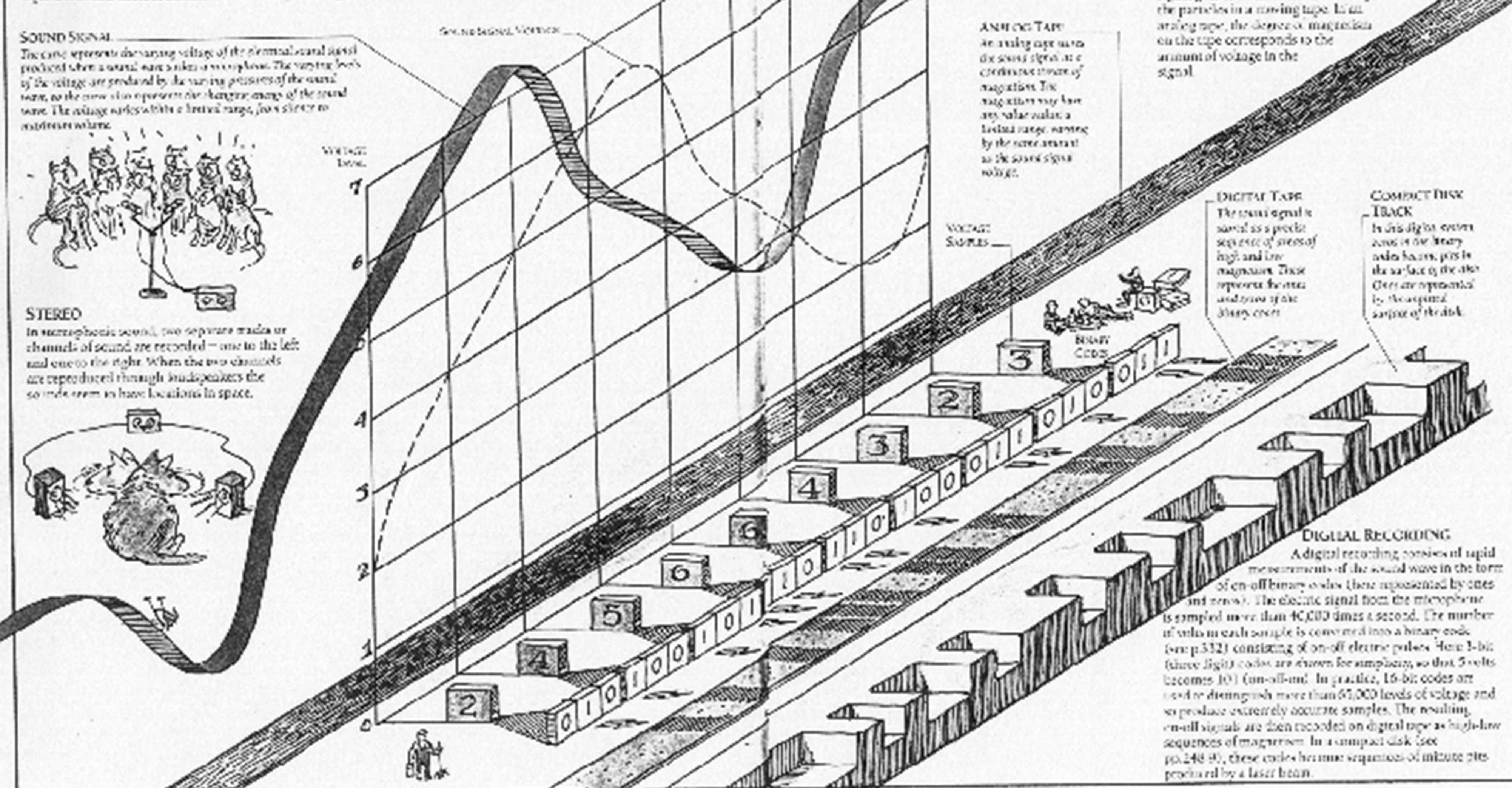
Digital Signal Acquisition

- 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 $2^{12} = 4096$)

FPT ISBN 0-395-42857-2 >$29.95

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 stores 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 stored 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 ones in the binary codes become pits in the surface of the disk. Zeros 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

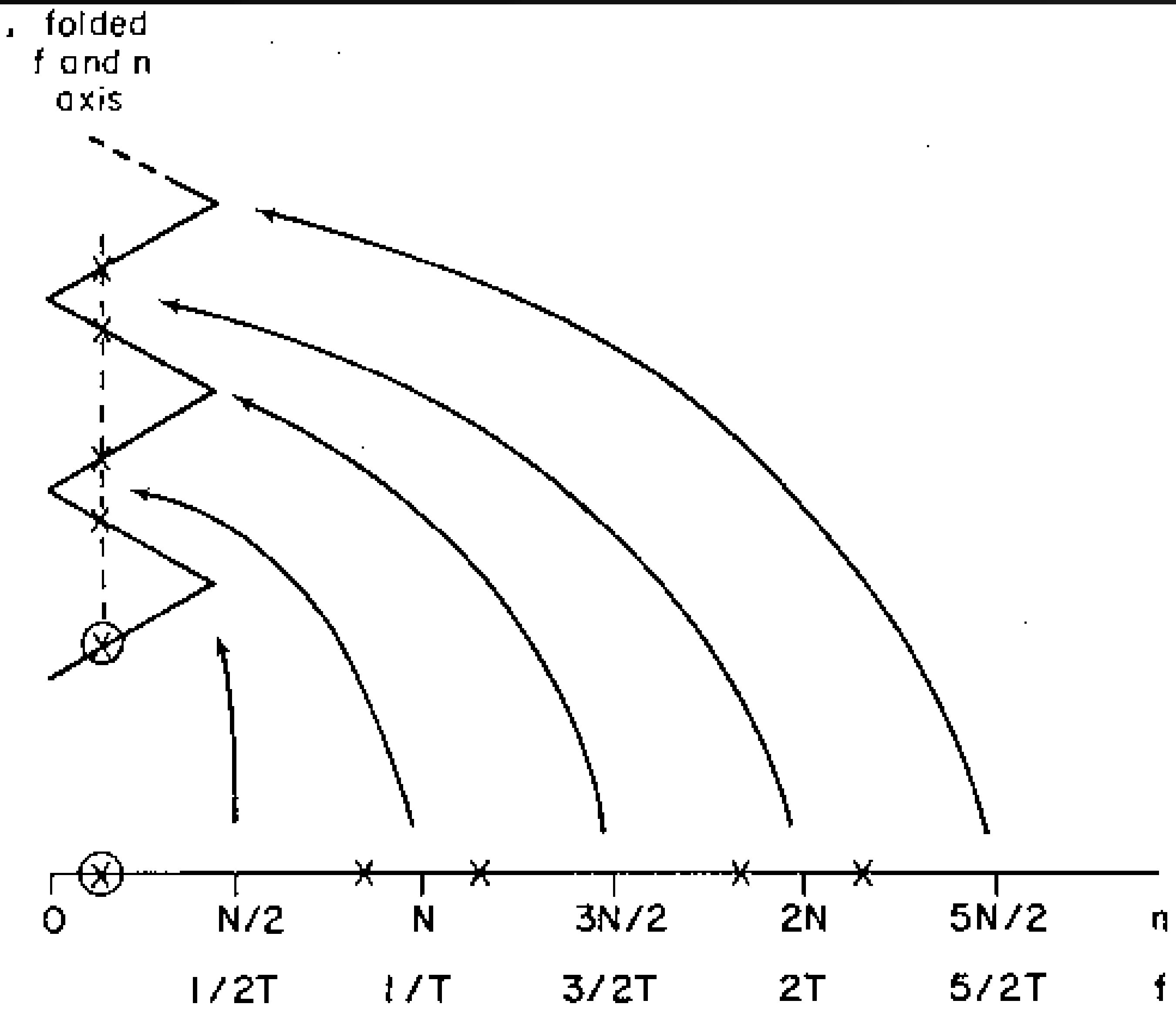
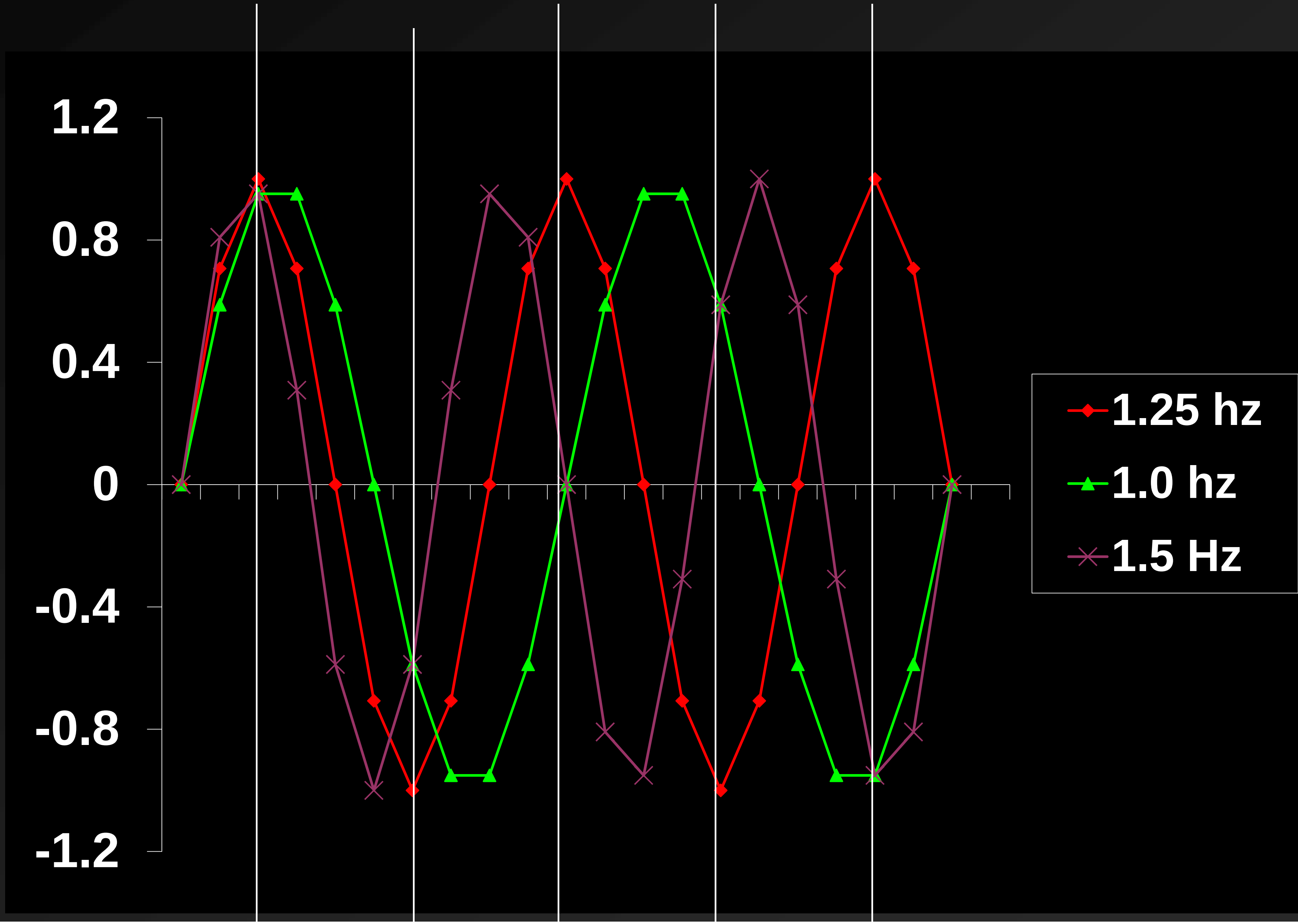
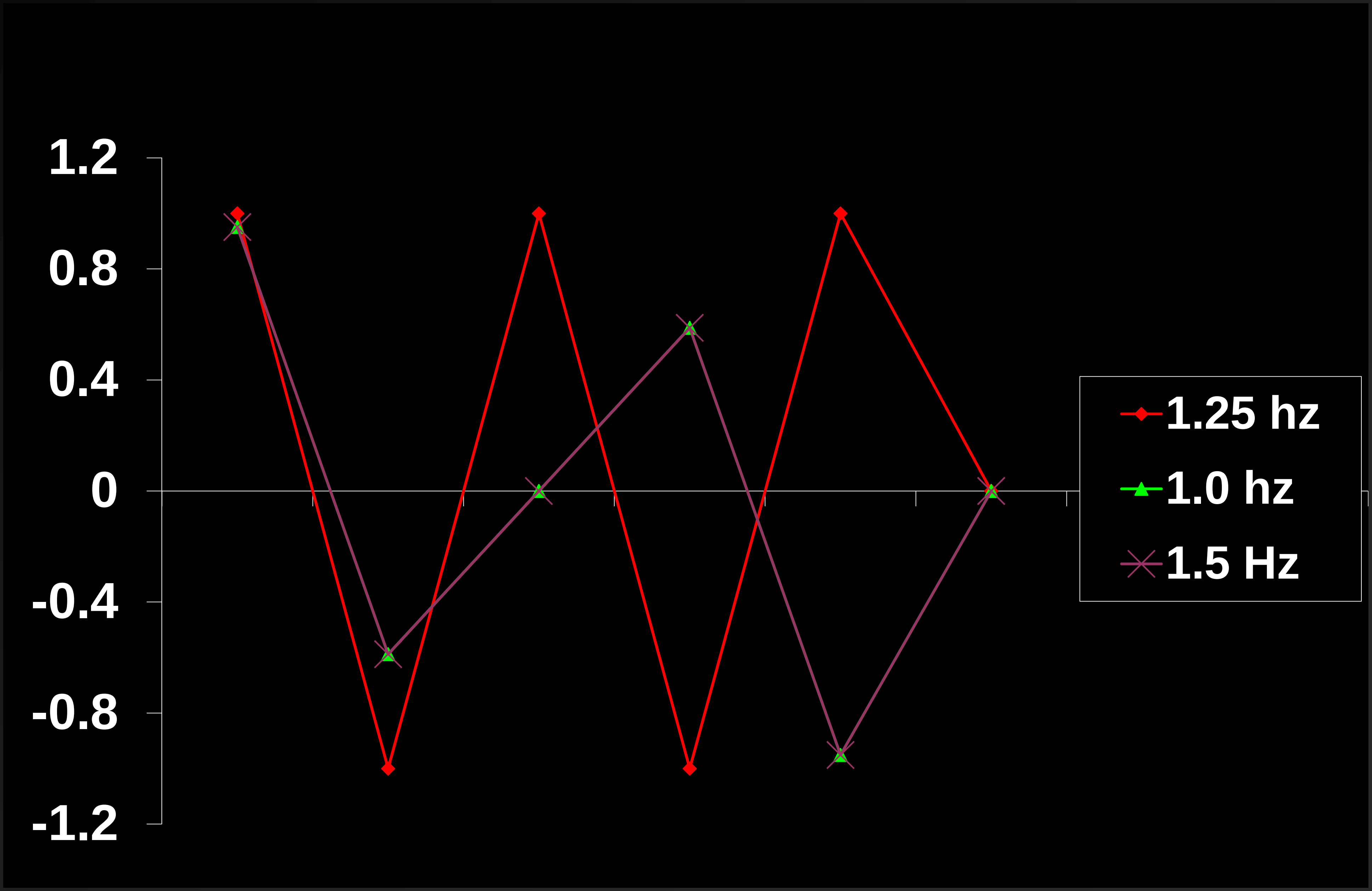


Fig. 3.2. The accordionlike folding of the frequency (or n) axis due to sampling of a continuous signal. Frequency components of the original signal marked with x's on the f axis are interpreted in the sampled version as belonging to the lowest frequency, an encircled x.

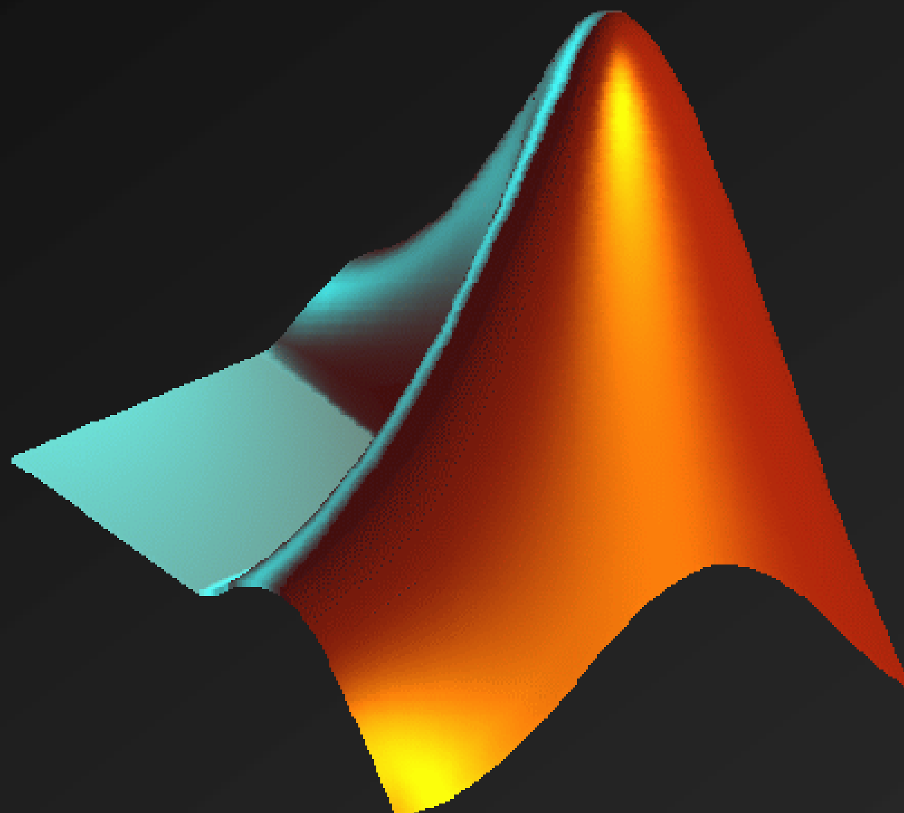
Aliasing Demo (Part 1, 10 Hz Sampling Rate)



Aliasing Demo (Part 2, 2.5 Hz Sampling Rate)



Matlab Demo of Aliasing



Solutions to Aliasing

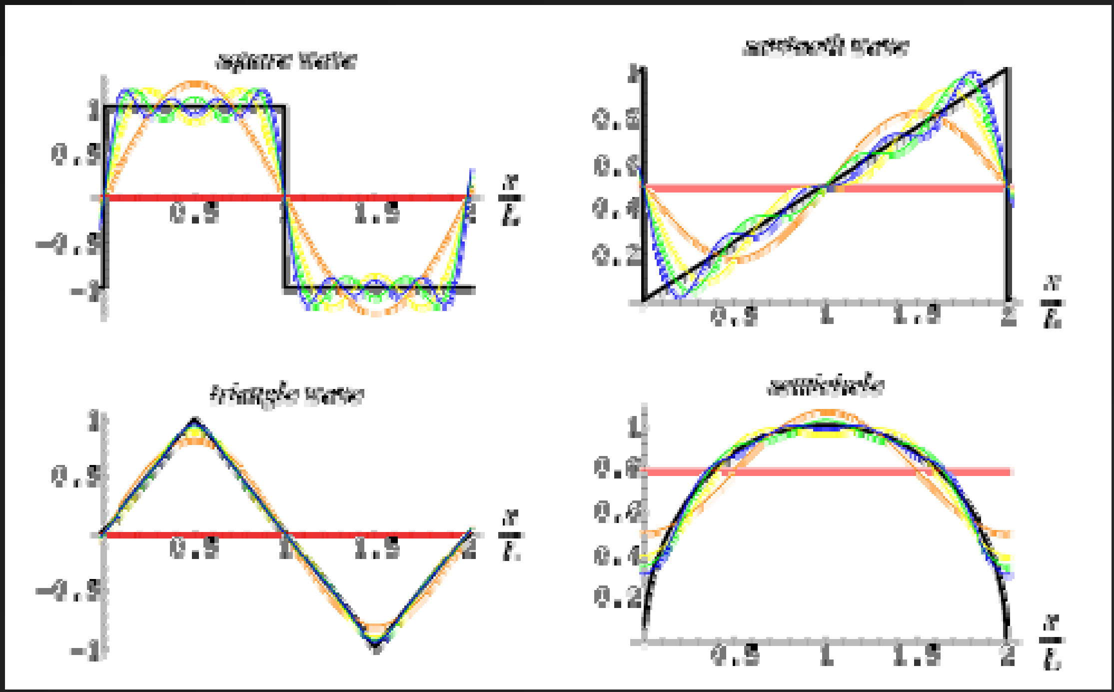
- Sample very fast
- Use anti-aliasing filters
- KNOW YOUR SIGNAL!

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

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



For nice demo, see http://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.
- Psychophysiologists often interested in amplitude component:
  - Power spectrum; for each frequency n/T

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

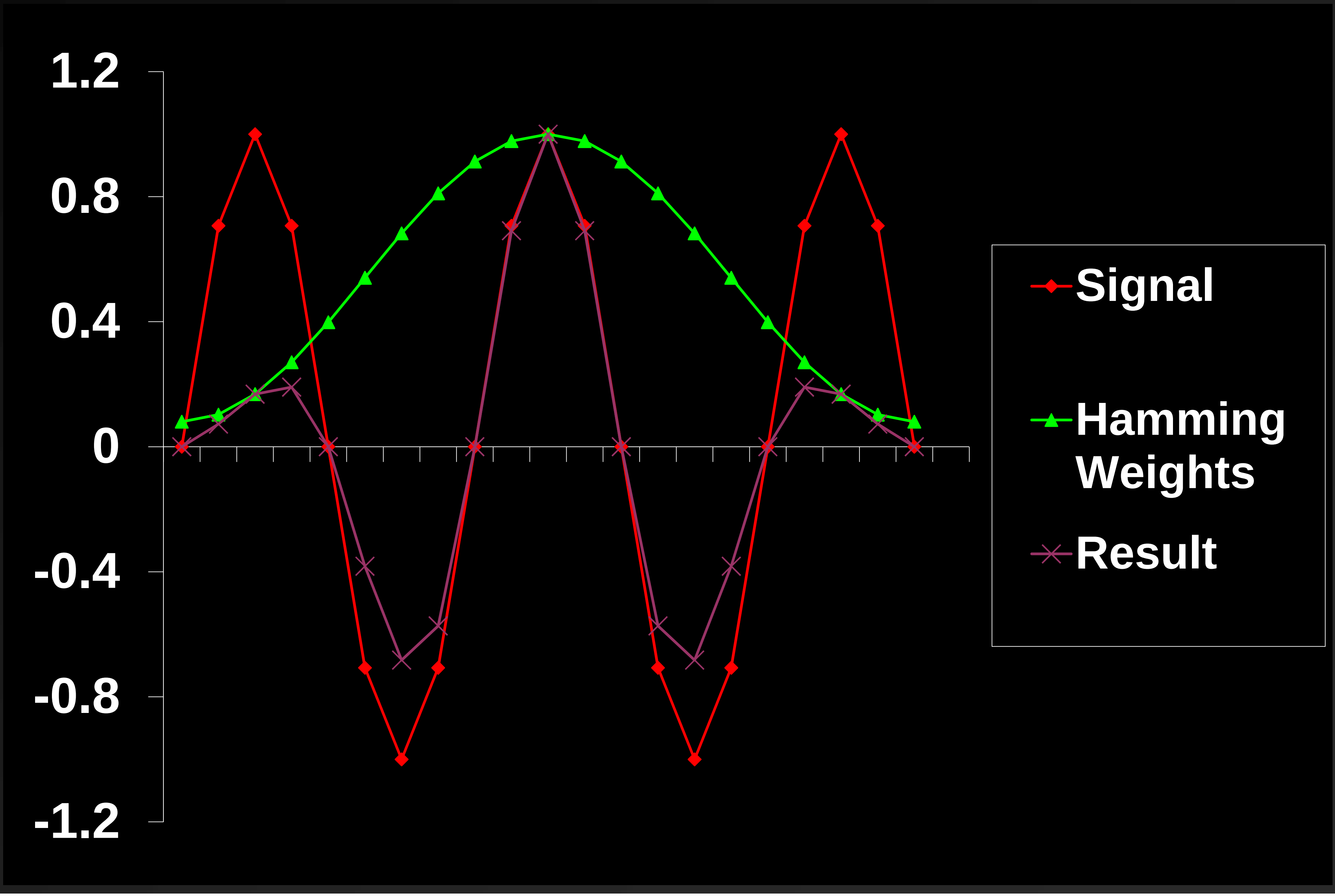
  - Amplitude Spectrum (may conform better to assumptions of statistical procedures); for each frequency n/T

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

Preventing Spectral Leakage

- Use windows
  - not Micro$oft Windows
  - Hamming
  - Hanning
  - Cosine
  - Etc.

Hamming Demo



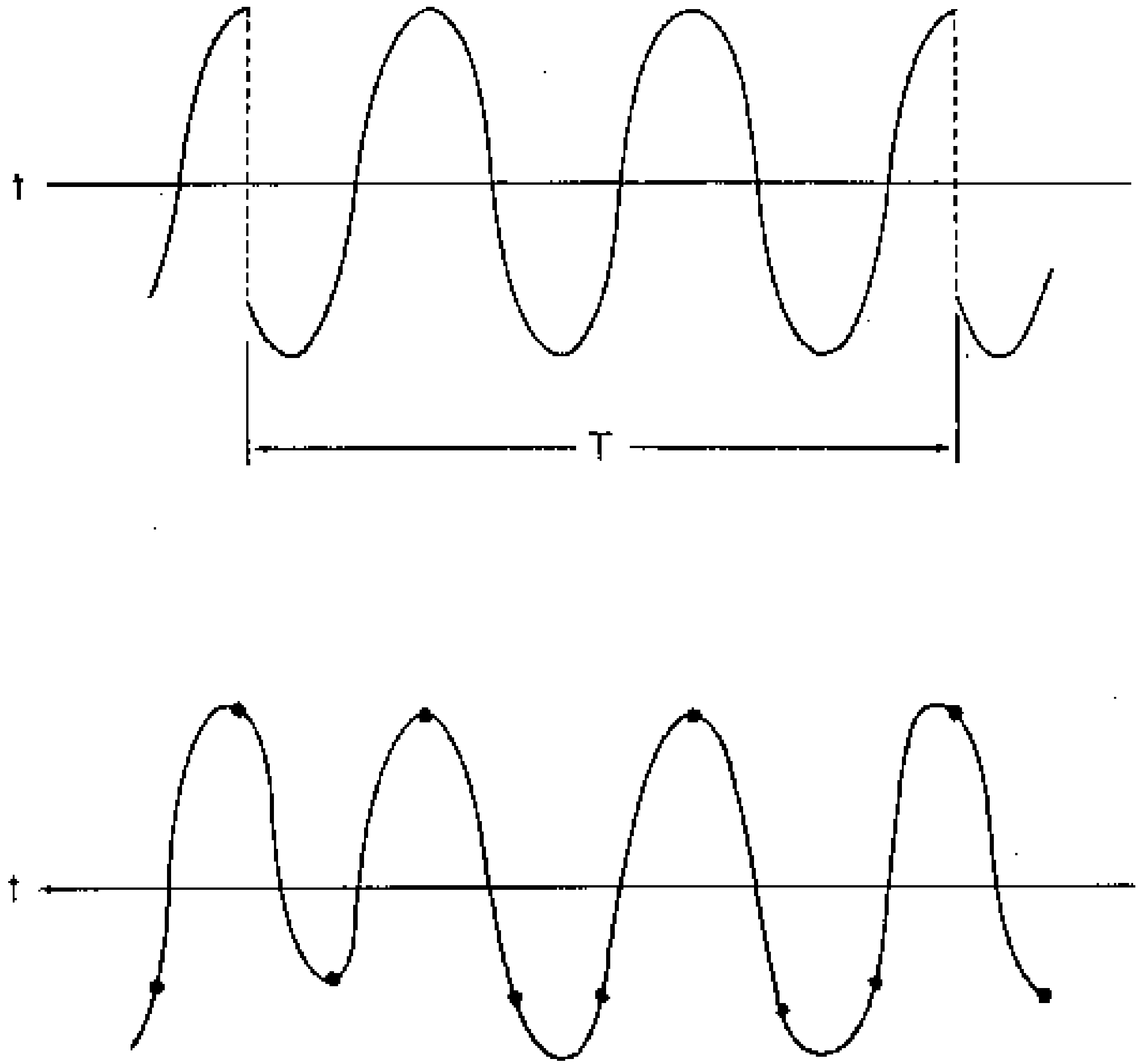
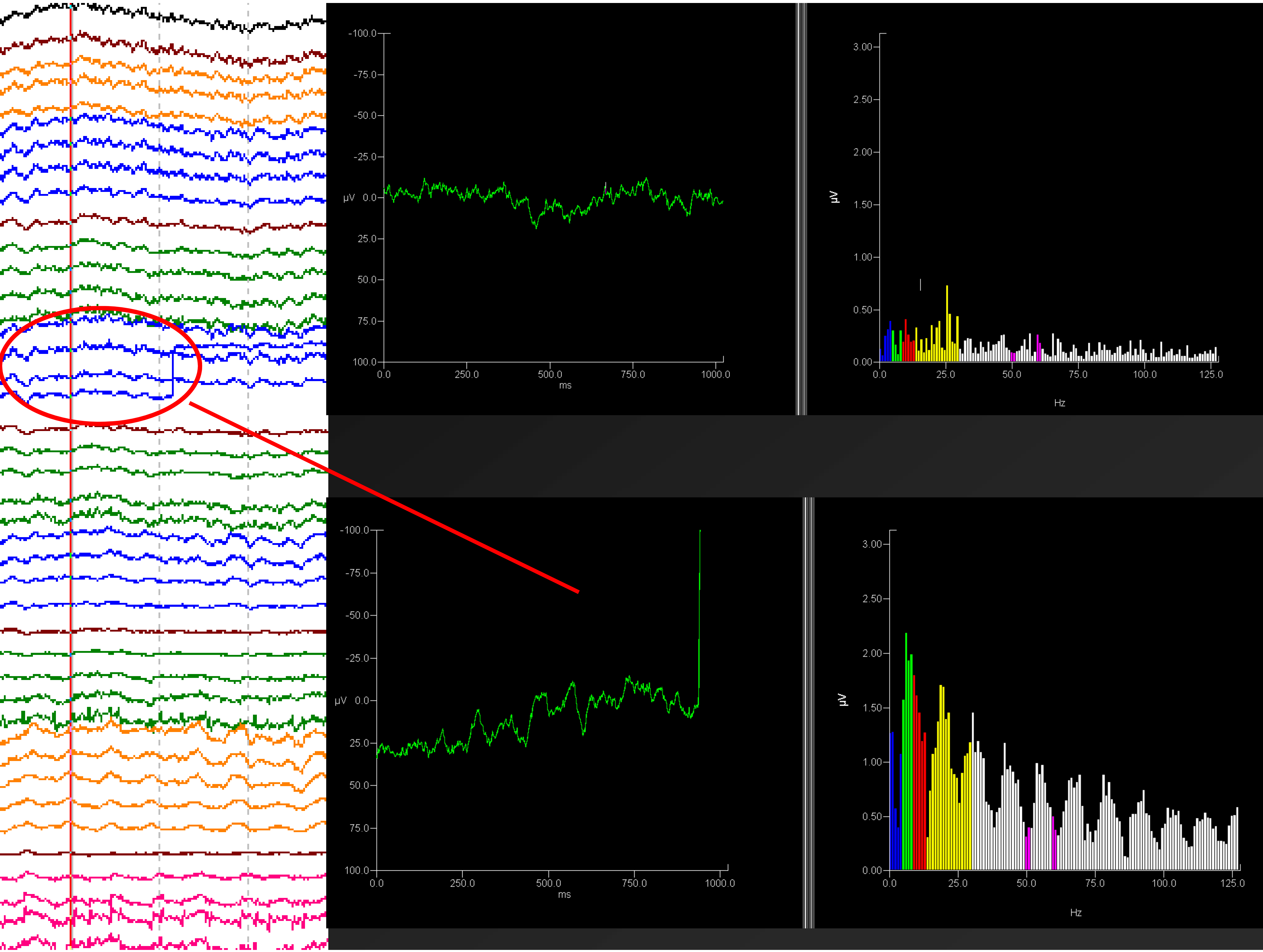


Fig. 3.3. Top, a periodicized segment of a cosine wave. T is the observation time and 3T/8 the period of the wave. Note the discontinuities at 0 and T. Bottom, a continuous and periodic band-limited wave drawn through the sample points Δ = T/16 sec apart.

Matlab Demo of Hamming Window

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

Frequency-domain EEG applications and methodological considerations

Applications

- Emotion Asymmetries
  - Lesion findings
    - Catastrophic reaction (LH)
    - RH damage show a belle indifference
  - EEG studies
    - Trait (100+ studies)
    - State (oodles more studies)

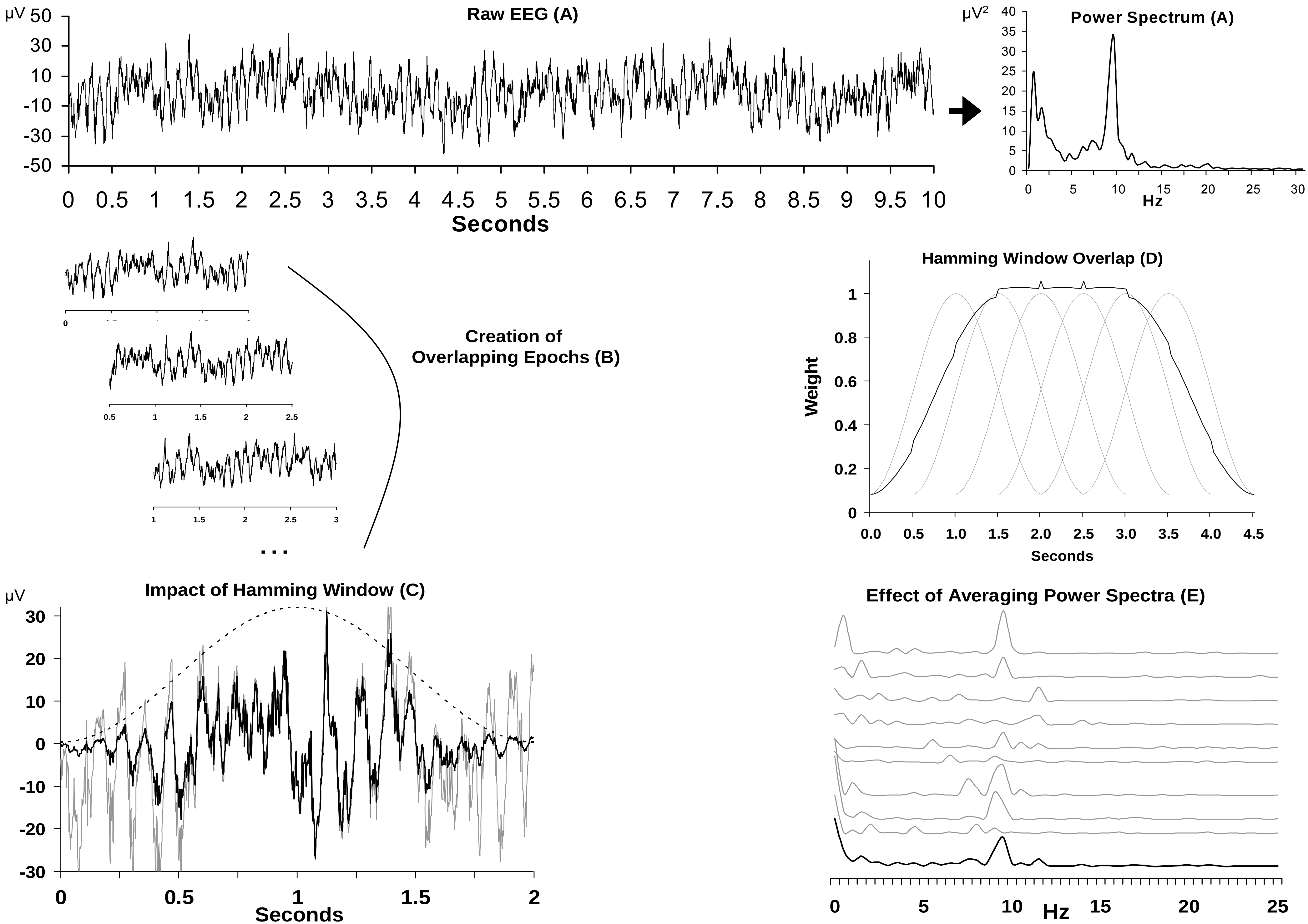
Types of Studies

- Trait
  - Resting EEG asymmetry related to other traits (e.g. BAS)
  - Resting EEG asymmetry related to psychopathology (e.g. depression)
  - Resting EEG asymmetry predicts subsequent emotional responses (e.g. infant/mom separation)
- State
  - State EEG asymmetry covaries with current emotional state (e.g., self report, spontaneous emotional expressions)

Trait, Occasion, and State variance

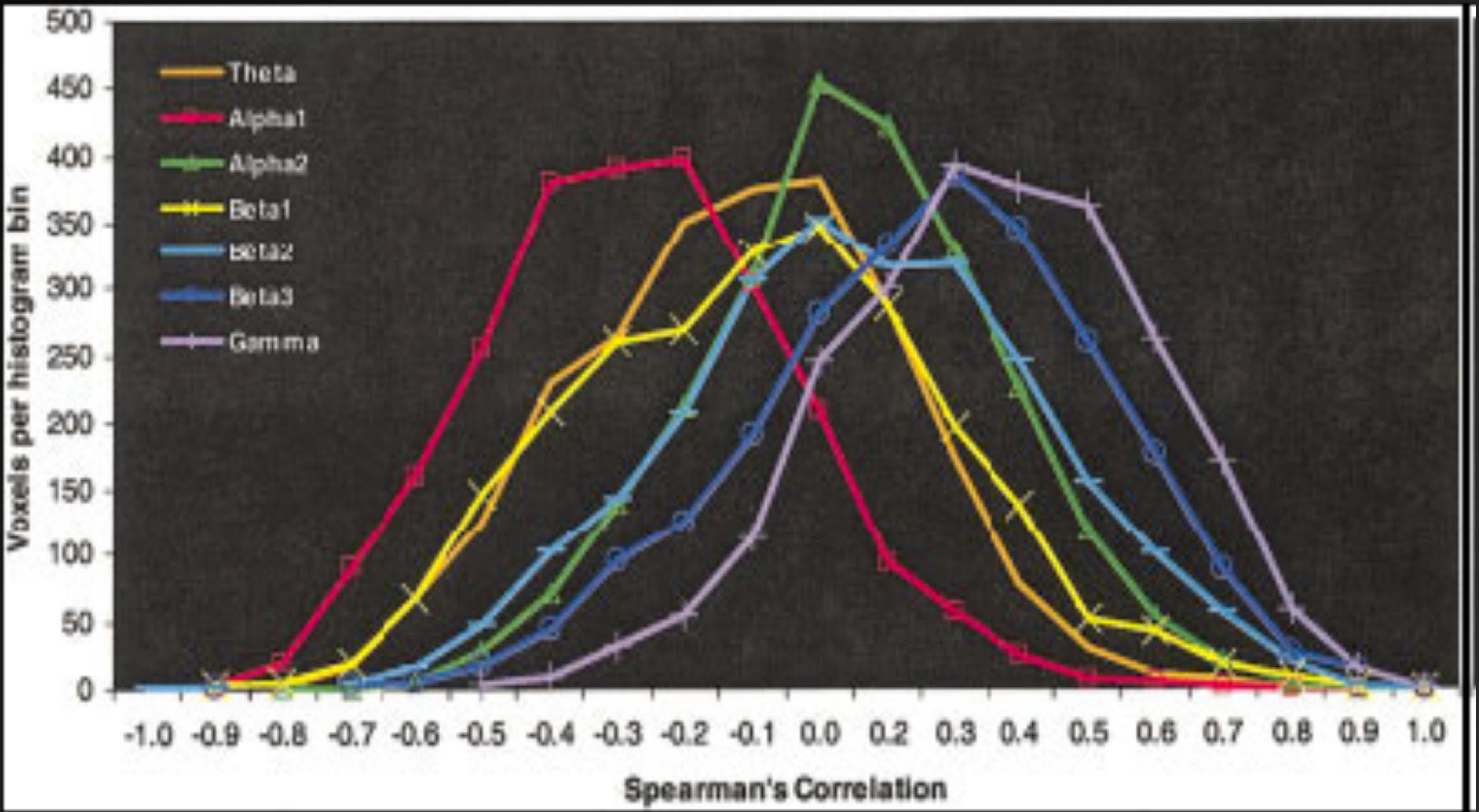
- Three sources of reliable variance for EEG Asymmetry
  - *Stable trait consistency* across multiple assessments
  - *Occasion-specific* variance
    - reliable variations in frontal asymmetry across multiple sessions of measurement
    - may reflect systematic but unmeasured sources such as current mood, recent life events and/or factors in the testing situation.
  - *State-specific* variance
    - changes within a single assessment that characterize
      - the difference between two experimental conditions
      - the difference between baseline resting levels and an experimental condition.
      - conceptualized as proximal effects in response to specific experimental manipulations
      - should be reversible and of relatively short duration
- Unreliability of Measurement (small)

Allen, Coan, & Nazarian 2004



Raw EEG (A)
μV
Seconds
Power Spectrum (A)
μV2
Hz
Creation of
Overlapping Epochs (B)
Hamming Window Overlap (D)
Weight
Seconds
Impact of Hamming Window (C)
μV
Seconds
Effect of Averaging Power Spectra (E)
Hz

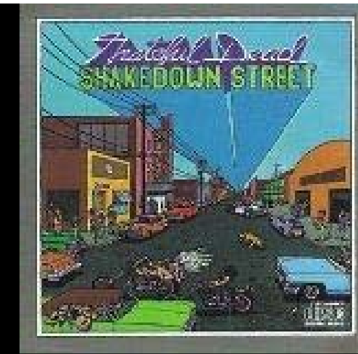
Alpha Vs Activity Assumption (AAA)

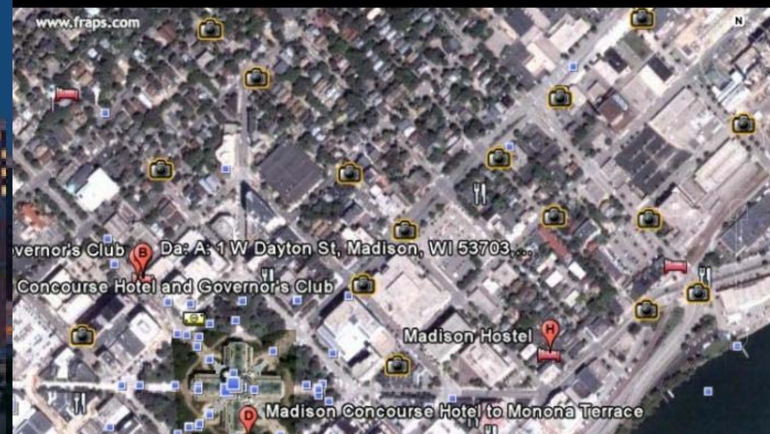


Oakes et al, 2004, *Human Brain Mapping*

EEG Asymmetry, Emotion, and Psychopathology

1978





EIGHTEENTH ANNUAL MEETING
SOCIETY FOR PSYCHOPHYSIOLOGICAL RESEARCH

The Eighteenth Annual Meeting of The Society for Psychophysiological Research was held at The Concourse Hotel in downtown Madison, Wisconsin, September 15, 16, 17, and 18, 1978. Members of the Program Committee were: Rafael Klorman and Ted Weerts (Co-Chairmen), Michael Coles, Don Fowles, Linda Gannon, Jennings, Rathe Karrer, Michael Nelson, Arne Öhman, Leonard Salzman, and David Siddl

As in recent years, the bulk of the research reports were given and discussed informally at Friday and Sunday evenings, September 15 and 17. In addition, research reports were presented sessions on Saturday and Monday mornings, and others were included in the Display and Dis which ran in tandem with the meetings on Saturday from 8:30 to 5:00. Several symposia, workshops were also included in this year's program.

Following are the abstracts of research reports presented and discussed during the Paper Sessi Display and Discussion poster session.

PAPER SESSION II

"During positive affect, the frontal leads display greater relative left hemisphere activation compared with negative affect and vice versa"

202 SPR ABSTRACTS, 1978 *Vol. 16, No. 2*

PAPER SESSION II

1. Silverstein, L. D., & Graham, F. K. (University of Wisconsin - Madison) **Selective attention effects on reflex activity.** Bohlin and Graham (1977) found that reflex blinking, unlike spontaneous blinking, was facilitated in association with cardiac deceleration when subjects were required to attend to the reflex-eliciting stimulus. The enhancement of sensory processing on the attended channel was proposed as an explanation for the facilitation. If so, directing attention to a different channel should remove the facilitation. This hypothesis was tested in two experiments analogous to the Bohlin and Graham (1977) studies. The critical change was requiring subjects to attend to a stimulus in a modality orthogonal to that of the reflex-eliciting stimulus.

In each experiment, 15 college students received 60- or 120-msec, low-intensity, electrotactile stimuli concurrently with a 50-msec auditory startle pulse. A warning tone preceded electrotactile and startle stimuli by 2 sec in the experimental conditions, while in the control conditions the two stimuli were presented without warning. Subjects' task was to discriminate electrotactile stimulus duration.

As in earlier intramodal studies, the warning tone elicited significant cardiac deceleration during the warning intervals of both experiments. Significantly better discrimination occurred on warned than unwarned control trials (Exp. 1—73.7% vs 60.3%; Exp. 2—73.2% vs 49.5%). Reflex blink latency was also significantly facilitated in both experiments. However, unlike the intramodal studies, blink magnitude was reduced. A small reduction in Experiment 1 was not a reliable effect, but increased startle pulse intensity in Experiment 2 resulted in a larger and significant reduction.

The hypothesis that reflexive motor activity is influenced by selective sensory enhancement was clearly supported. The results are interpreted with respect to a general theory of orienting and reflex control.

(Supported by the Grant Foundation, by an NSF grant BMS75-17075, and by a Research Scientist Award K3-MH21762 and a Fellowship Award MH07198-01 from NIMH)

2. Washton, A. M. (New York Medical College) **Autonomic and stimulus control of conditional cardiac rate responses in rhesus monkeys.** Conditional cardiac rate responses (cardiac CRs) of 6 rhesus monkeys were examined under systematic and broad manipulation of the temporal variable of CS-US interval length. A Pavlovian delay conditioning procedure was employed in which the duration of a visual conditional stimulus (CS) preceding an aversive electric-shock unconditional stimulus (US) was increased progressively from 2 to 120 sec for each animal. At each of 8 differing CS-US interval conditions, selective autonomic blocking agents were administered to assess the relative roles of the sympathetic and parasympathetic branches of the autonomic nervous system in the elaboration of observed cardiac rate CRs. Each subject was tested both in the absence of any drugs and under: 1) sympathetic blockade with propranolol, 2) parasympathetic blockade with atropine, 3) double blockade with a combination of propranolol and atropine, and 4) ganglionic blockade with chlorisondamine.

The within-CS waveform of the cardiac rate CR was least consistent at the first 3 CS-US intervals of 2–6 sec, where instances of accelerative, decelerative, and biphasic HR patterns were observed during CS both within and among subjects, with the direction of response varying with the level of HR just prior to CS onset. By contrast, at CS-US intervals from 10 to 120 sec, a stable and consistent biphasic HR pattern of initial acceleration followed by deceleration was uniformly observed during CS despite continued wide fluctuations in pre-CS HR.

Both accelerative and decelerative HR changes within the CS-US interval were eliminated almost entirely by parasympathetic blockade alone, combined sympathetic and parasympathetic blockade, and ganglionic blockade. Sympathetic blockade alone left large HR changes within the CS-US interval, with CR deceleration often facilitated relative to pre-drug. These effects were similar across the full range of CS-US intervals employed, and whether the pre-drug form of the cardiac CR was monophasic or biphasic. The unconditional HR response (UCR) to shock was similar in form to the CR, consisting of an initial accelerative and subsequent decelerative component, and was similarly affected by the pharmacological agents, although the UCR was less suppressed by the drugs.

3. Davidson, R. J. (State University of New York at Purchase), **Schwartz, G. E.** (Yale University), **Saron, C., Bennett, J.** (State University of New York at Purchase), **& Goleman, D. J. Frontal versus parietal EEG asymmetry during positive and negative affect.** A variety of data suggest that positive and negative affect may be differentially lateralized in the human brain. This report describes an experiment which explored the differential effect of positive versus negative affect on parietal and frontal brain regions. Seventeen right-handed subjects were exposed to portions of a television show judged to vary in emotional content. Subjects were asked to press down on a pressure-sensitive knob according to how much they disliked and to let up according to how much they liked the program, with hand use counterbalanced across subjects. These pressure changes, along with EEG filtered for 8–13 Hz recorded from F_4, F_3, P_4 and P_3 referenced to C_z were digitized and printed every 30 sec. Two epochs representing the most positively and most negatively judged segments were chosen for analysis on the basis of each subject's ratings and were compared on parietal and frontal asymmetry as reflected in the ratio R−L/R+L alpha. The results revealed a significant Region (Frontal vs Parietal) × Affective Valence (positive vs negative) interaction. During positive affect, the frontal leads display greater relative left hemisphere activation compared with negative affect and vice versa. Parietal asymmetry does not discriminate between these conditions, but does show right hemisphere activation during both.

A second experiment was conducted (Schwartz, Davidson, & Saron) during which self-generated positive and negative affective imagery served as the main inde-

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Left Hypofrontality in Depression

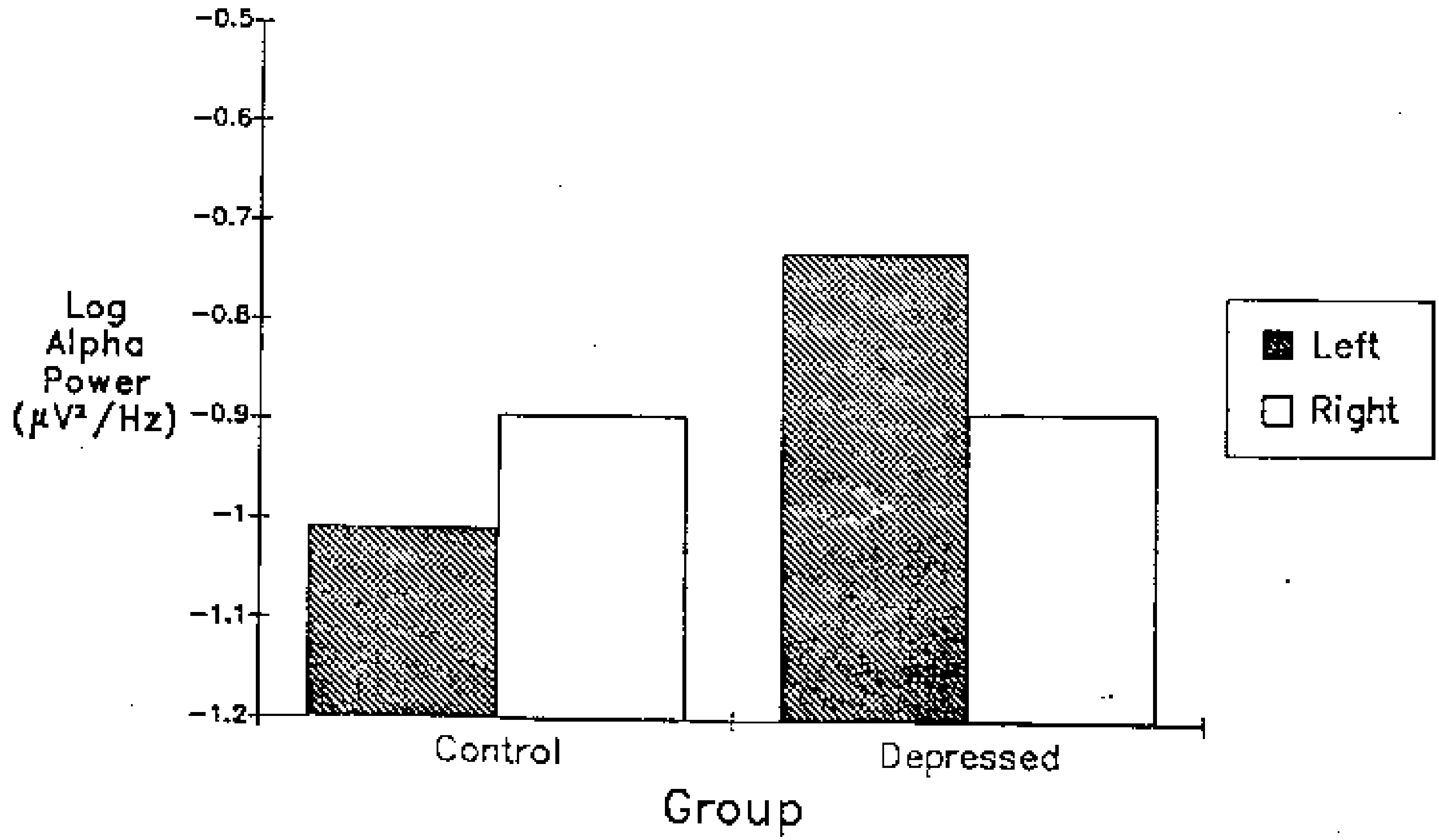
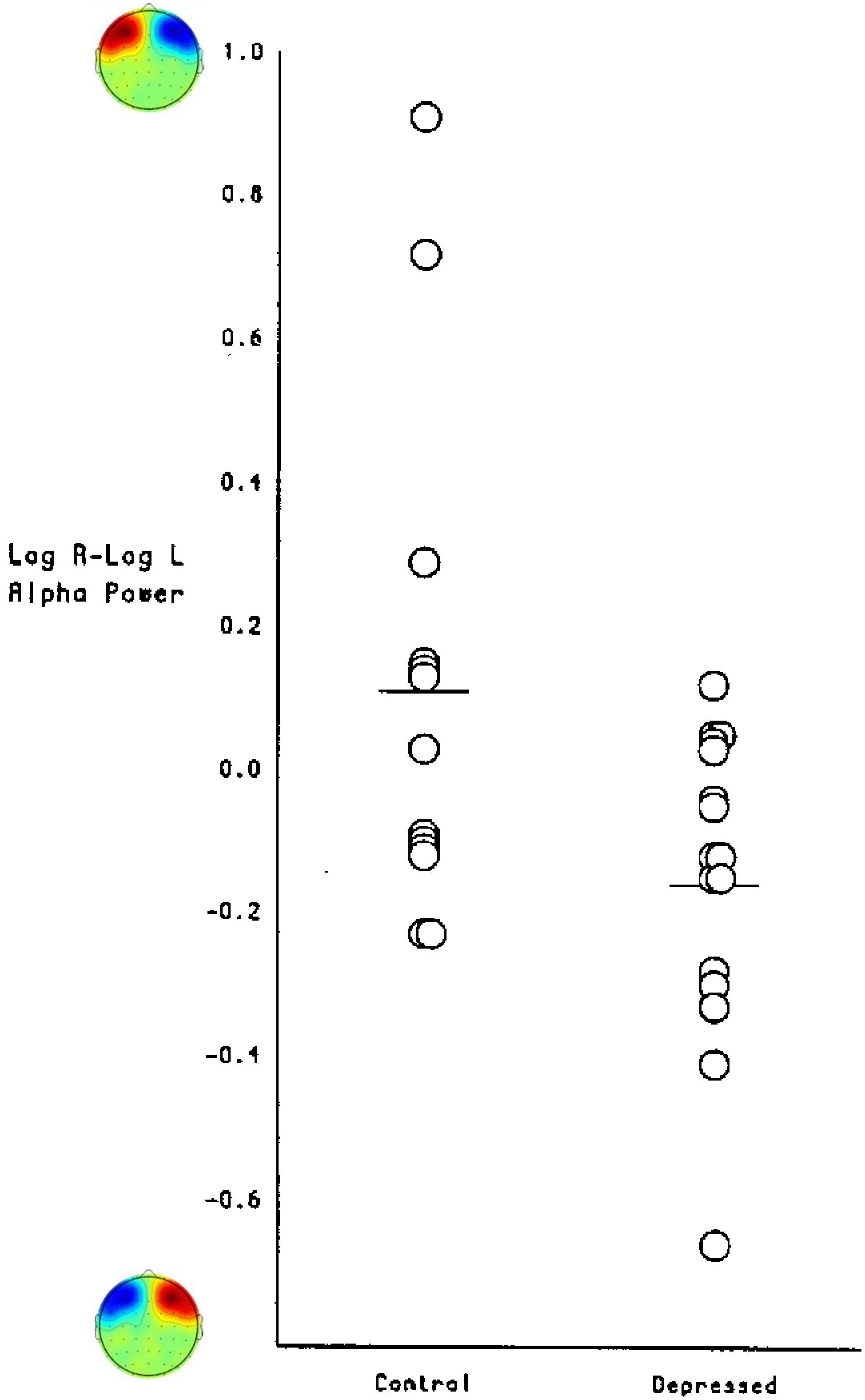


Figure 1. Mean log-transformed alpha (8–13 Hz) power (in $\mu V^2/Hz$) for Cz-referenced electroencephalograms (averaged across eyes-open and eyes-closed baselines), split by group and hemisphere, for the mid-frontal region. (Decreases in alpha power are indicative of increased activation.)

Henriques & Davidson (1991); see also, Allen et al. (1993), Gotlib et al. (1998); Henriques & Davidson (1990); Reid Duke and Allen (1998); Shaffer et al (1983)

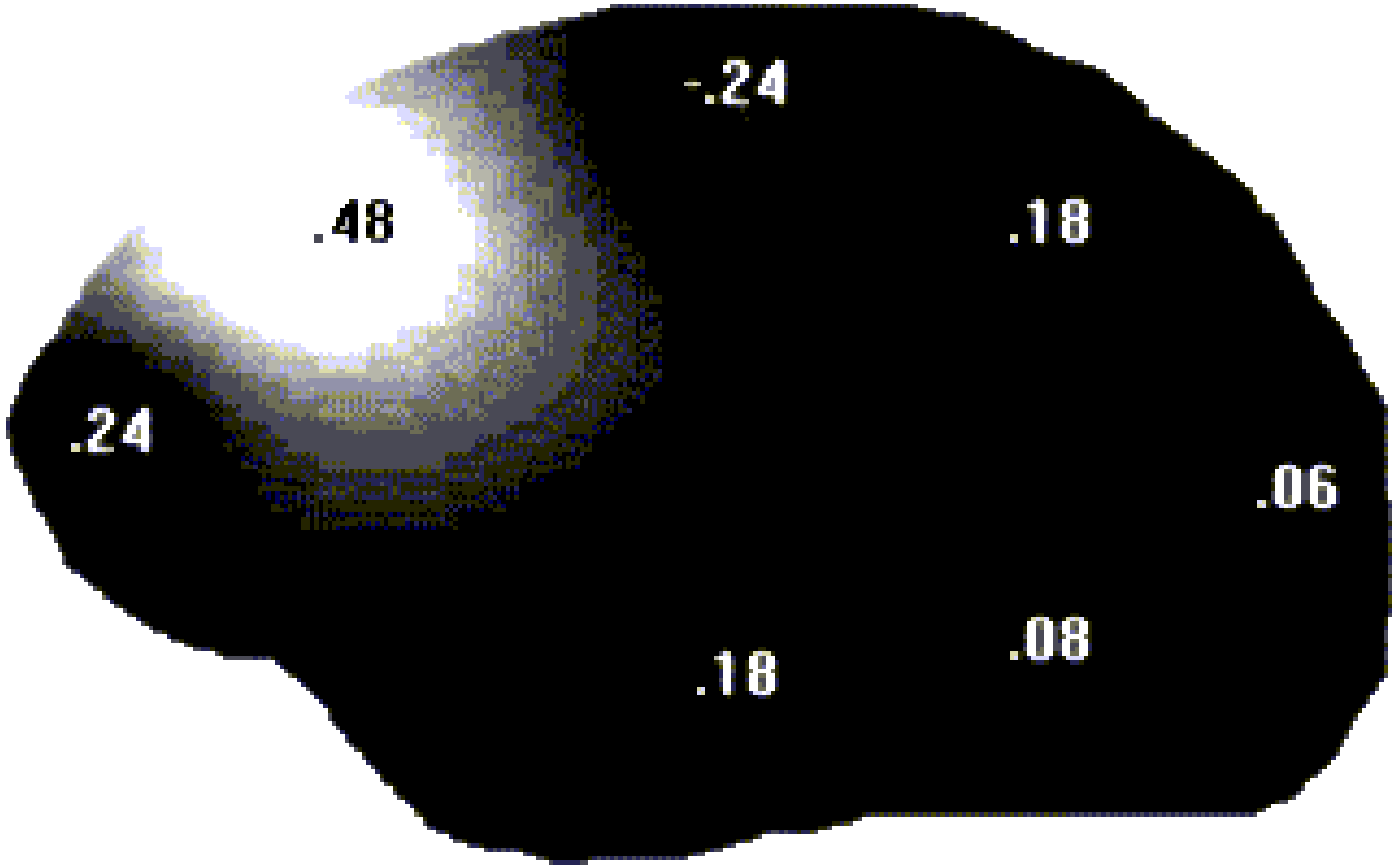
Individual Subjects' Data



Henriques & Davidson (1991)

Valence Vs Motivation

- Valence hypothesis
  - Left frontal is positive
  - Right frontal is negative
- Motivation hypothesis
  - Left frontal is Approach
  - Right frontal is Withdrawal
- Hypotheses are confounded
  - With possible exception of Anger



Correlation with alpha asymmetry (ln[right]-ln[left]) and trait anger. Positive correlations reflect greater left activity (less left alpha) is related to greater anger.

After Harmon-Jones and Allen (1998).

State Anger and Frontal Asymmetry

- Would situationally-induced anger relate to relative left frontal activity?

Harmon-Jones & Sigelman, *JPSP*, 2001

Method

- Cover story: two perception tasks – person perception & taste perception
- Person perception task – participant writes essay on important social issue; another ostensible participant gives written feedback on essay
- Feedback is neutral or insulting
  - negative ratings + “I can’t believe an educated person would think like this. I hope this person learns something while at UW.”

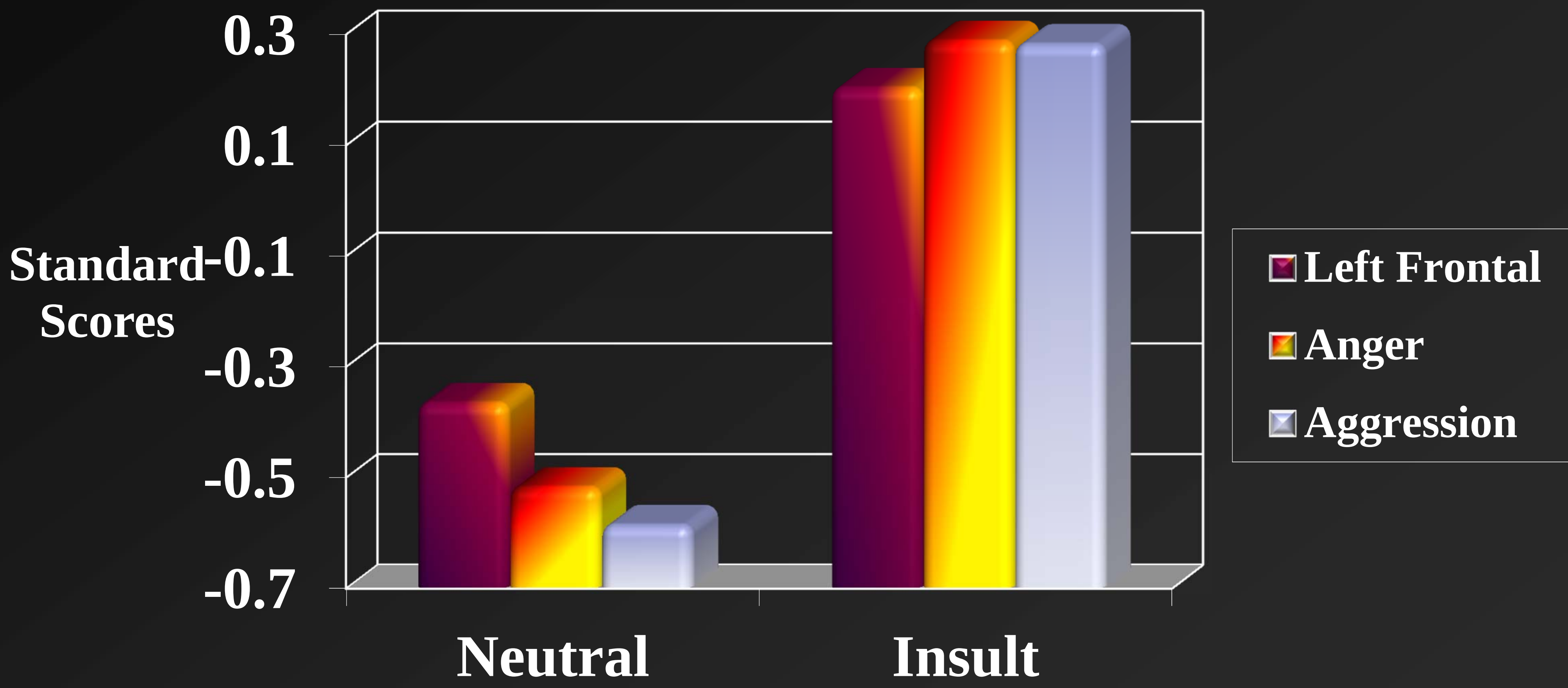
Harmon-Jones & Sigelman, *JPSP*, 2001

- Record EEG immediately after feedback
- Then, taste perception task, where participant selects beverage for other participant, "so that experimenter can remain blind to type of beverage."
- 6 beverages; range from pleasant-tasting (sweetened water) to unpleasant-tasting (water with hot sauce)
    - Aggression measure

Harmon-Jones & Sigelman, *JPSP*, 2001

Harmon-Jones & Sigelman, *JPSP*, 2001

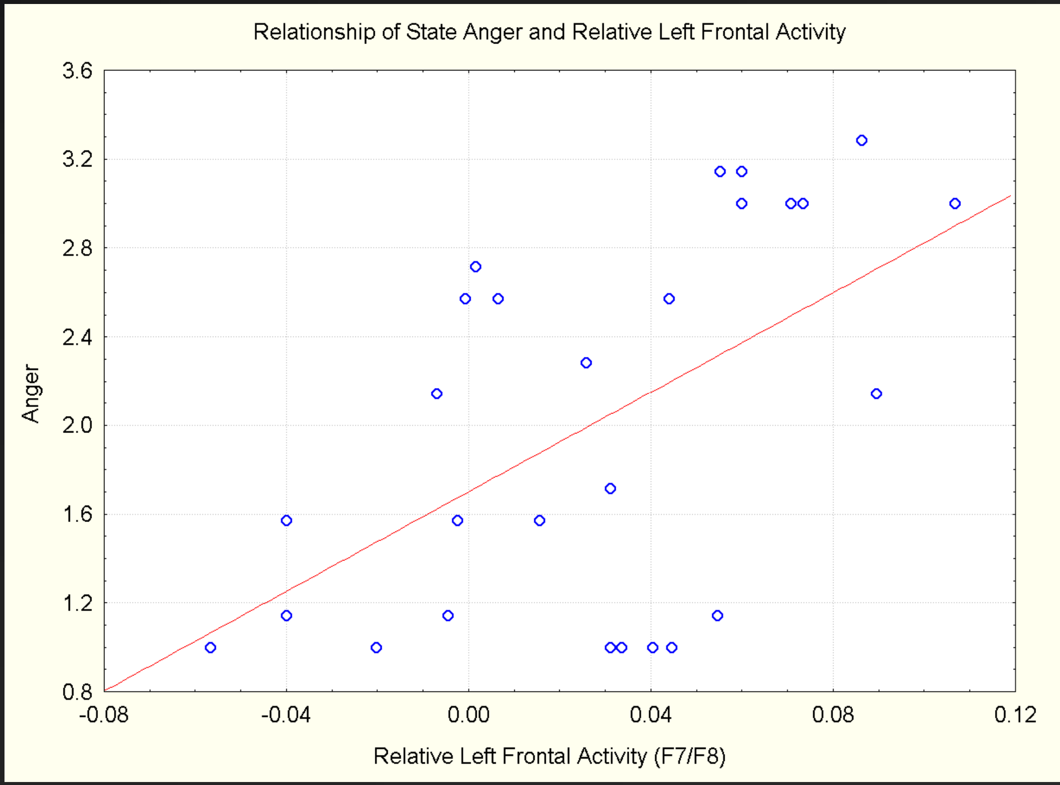
Relative Left Frontal, Anger, & Aggression as a Function of Condition



Harmon-Jones & Sigelman, *JPSP*, 2001

Frontal EEG asymmetry predicts Anger and Agression

- Not in Neutral condition … no relationship
- Strongly in Insult condition
  - r = .57 for anger
  - r = .60 for aggression
  - Note: partial r adjusting for baseline indiv diffs in asymmetry and affect



Harmon-Jones & Sigelman, *JPSP*, 2001

Manipulation of EEG
Peterson, Shackman, Harmon-Jones (2008)

- Hand contractions to activate contralateral premotor cortex
- Insult about essay (similar to Harmon-Jones & Sigelman, *JPSP*, 2001) followed by chance to give aversive noise blasts to the person who insulted them
- Hand contractions:
  - altered frontal asymmetry as predicted
  - Altered subsequent aggression (noise blasts)
- Asymmetry duruing hand contractions predicted aggression

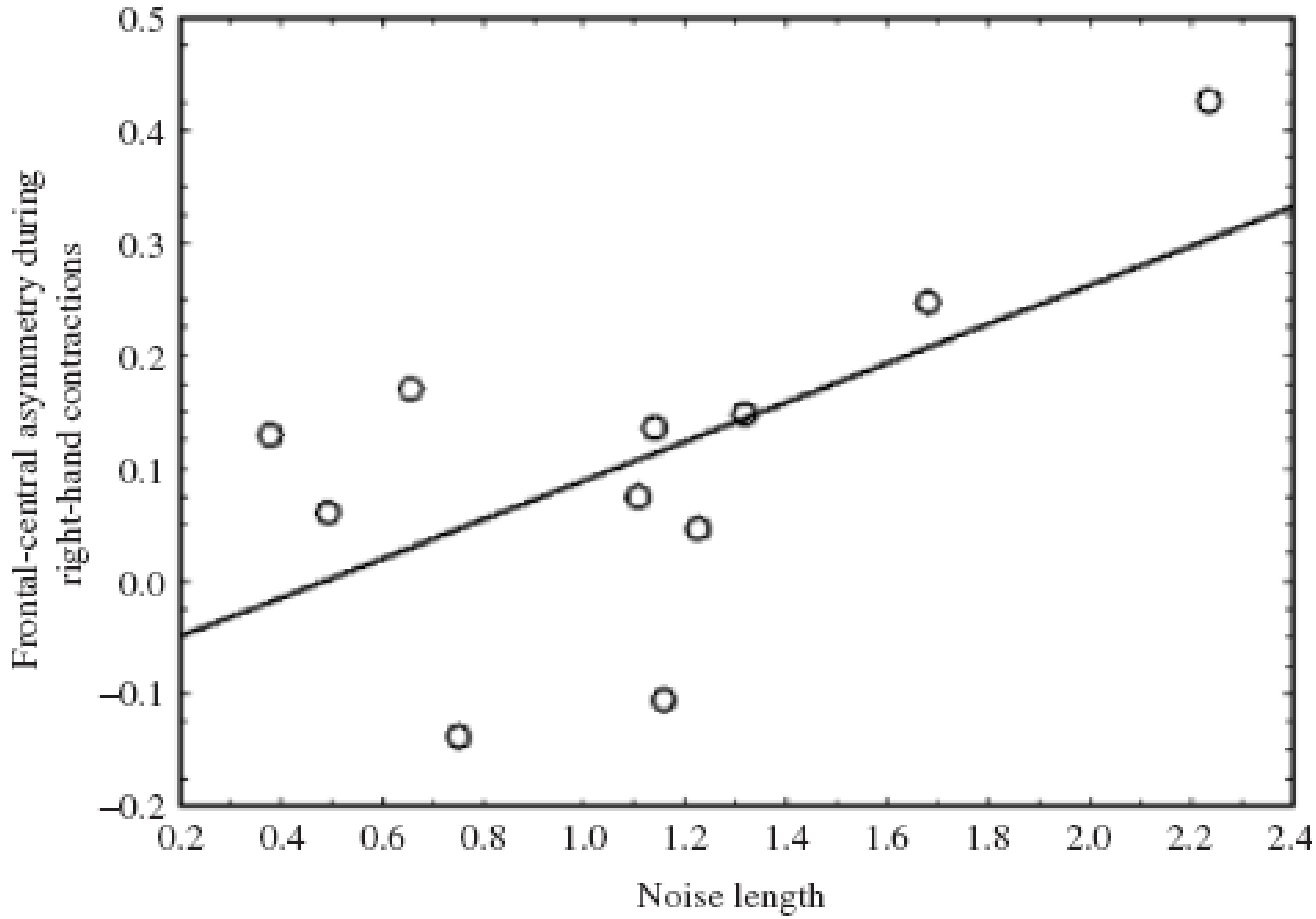


Figure 1. Relation between noise length and frontal-central asymmetry during right-hand contractions. Higher asymmetry scores indicate greater relative left than right activation.

Peterson, Shackman, Harmon-Jones (2008)

The BAS/BFS/Approach System

- **sensitive to signals of**
  - **conditioned reward**
  - **nonpunishment**
  - **escape from punishment**
- **Results in:**
  - **driven pursuit of appetitive stimuli**
  - **appetitive or incentive motivation**
  - **Decreased propensity for depression (Depue & Iacono, 1989; Fowles 1988)**

Motivational Styles and Depression

Behavioral Activation Scale

- Reward Responsiveness

  When I see an opportunity for something I like, I get excited right away.

- Drive

  I go out of my way to get things I want.

- Fun Seeking

  I'm always willing to try something new if think it will be fun.

Carver & White, 1994

Motivational Styles and Depression

$r = .45$

Mid-Frontal Asymmetry and BAS Scores

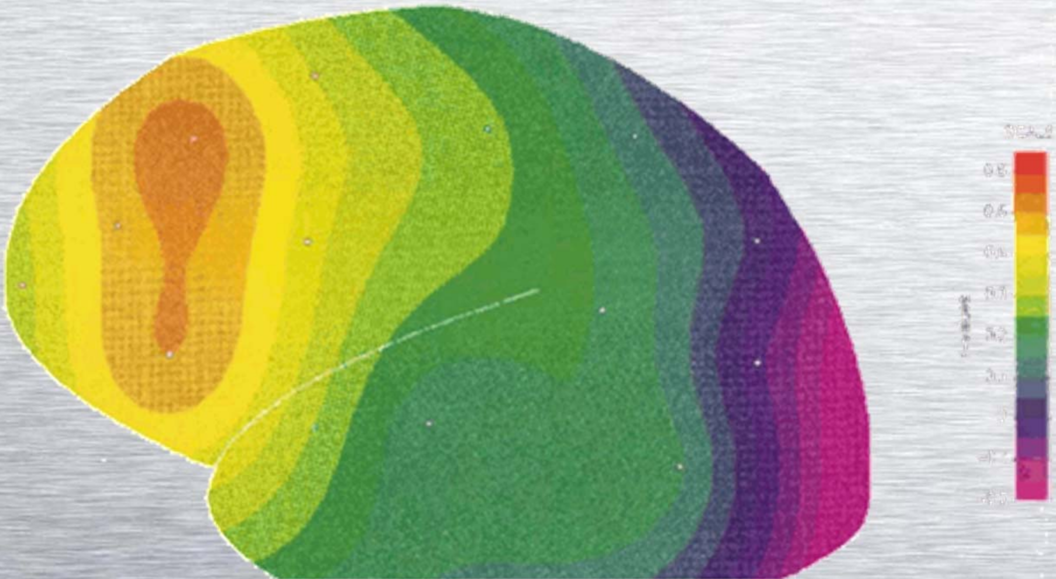
Mid-Frontal Asymmetry and PA Scores

$r = .00$

Harmon-Jones & Allen, 1997

Motivational Styles and Depression

Replications



Sutton & Davidson, 1997 Coan & Allen, 2003

Correlations with alpha asymmetry (ln[right]-ln[left]) and self-reported BAS scores (right) or BAS-BIS (left).

Positive correlations reflect greater left activity (less left alpha) is related to greater BAS scores or greater BAS-BIS difference

L>R Activity (R>L Alpha) characterizes:

- an approach-related motivational style (e.g. Harmon-Jones & Allen, 1997; Sutton & Davidson, 1997)
- higher positive affect (e.g. Tomarken, Davidson, Wheeler, & Doss, 1992)
- higher trait anger (e.g. Harmon-Jones & Allen, 1998)
- lower shyness and greater sociability (e.g. Schmidt & Fox, 1994; Schmidt, Fox, Schulkin, & Gold, 1999)

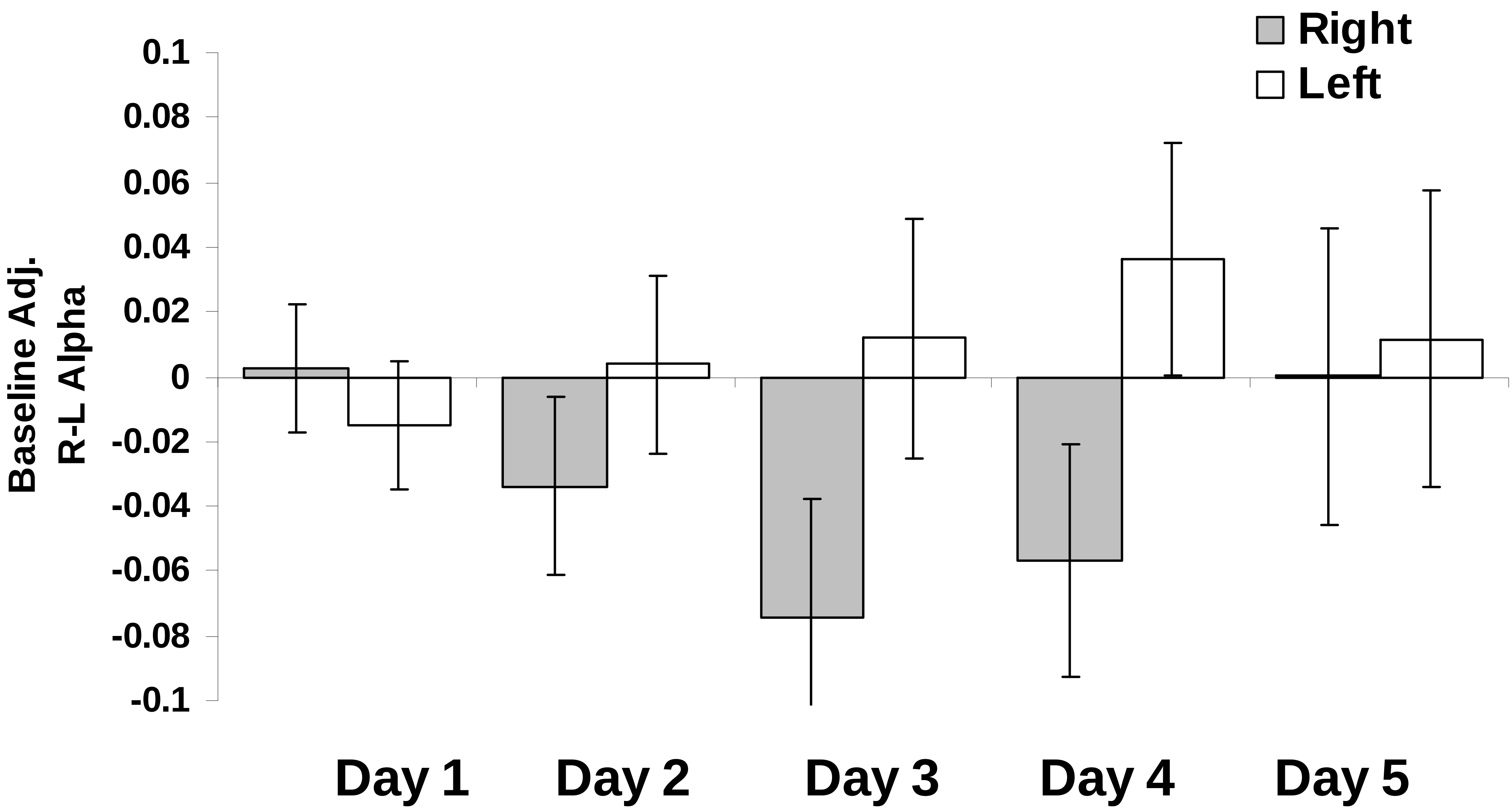
R>L Activity (L>R Alpha) characterizes:

- depressive disorders and risk for depression (e.g. Allen, Iacono, Depue, & Arbisi, 1993; Gotlib, Ranganath, & Rosenfeld, 1998; Henriques & Davidson, 1990; Henriques & Davidson, 1991 but see also Reid, Duke, & Allen, 1998
- certain anxiety disorders (e.g. Davidson, Marshall, Tomarken, & Henriques, 2000; Wiedemann et al., 1999)

Correlations ≠ Causality

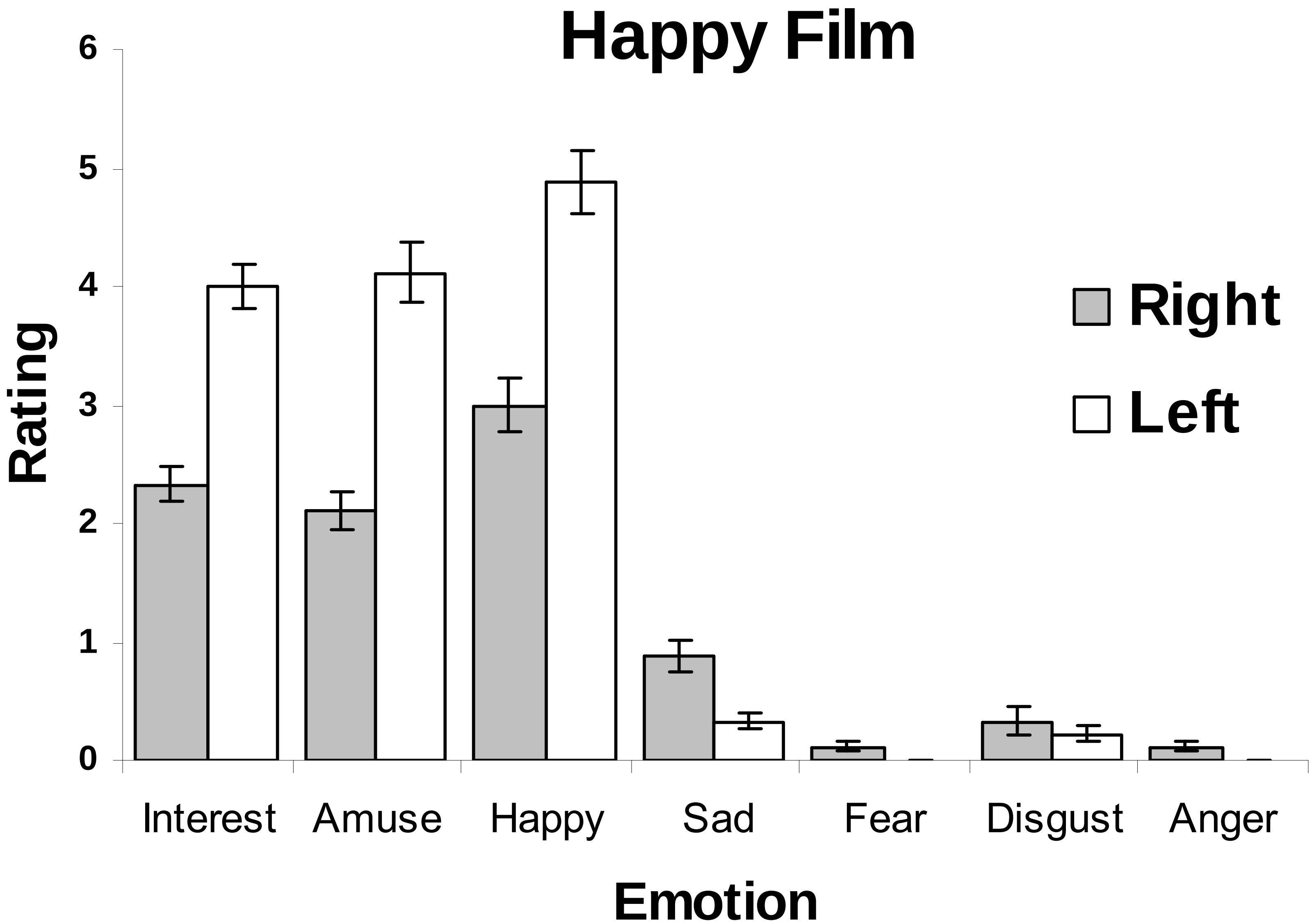
- Study to manipulate EEG Asymmetry
- Five consecutive days of biofeedback training (R vs L)
  - Nine subjects trained “Left”; Nine “Right”
  - Criterion titrated to keep reinforcement equal
- Tones presented when asymmetry exceeds a threshold, adjusted for recent performance
- Films before first training and after last training

Training Effects: Asymmetry Scores



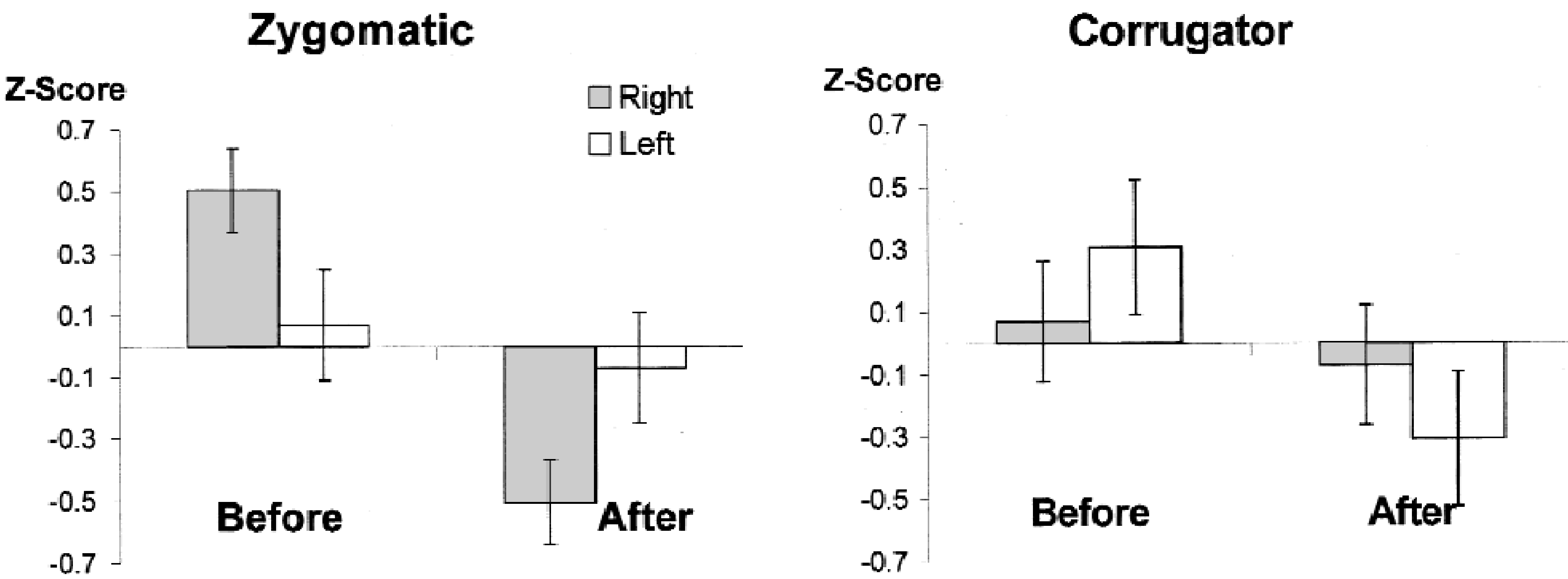
Manipulation of EEG asymmetry with biofeedback produced differential change across 5 days of training; Regression on Day 5

From Allen, Harmon-Jones, and Cavender (2001)



Despite no differences prior to training, following manipulation of EEG asymmetry with biofeedback subjects trained to increase left frontal activity report greater positive affect.

From Allen, Harmon-Jones, and Cavender (2001)

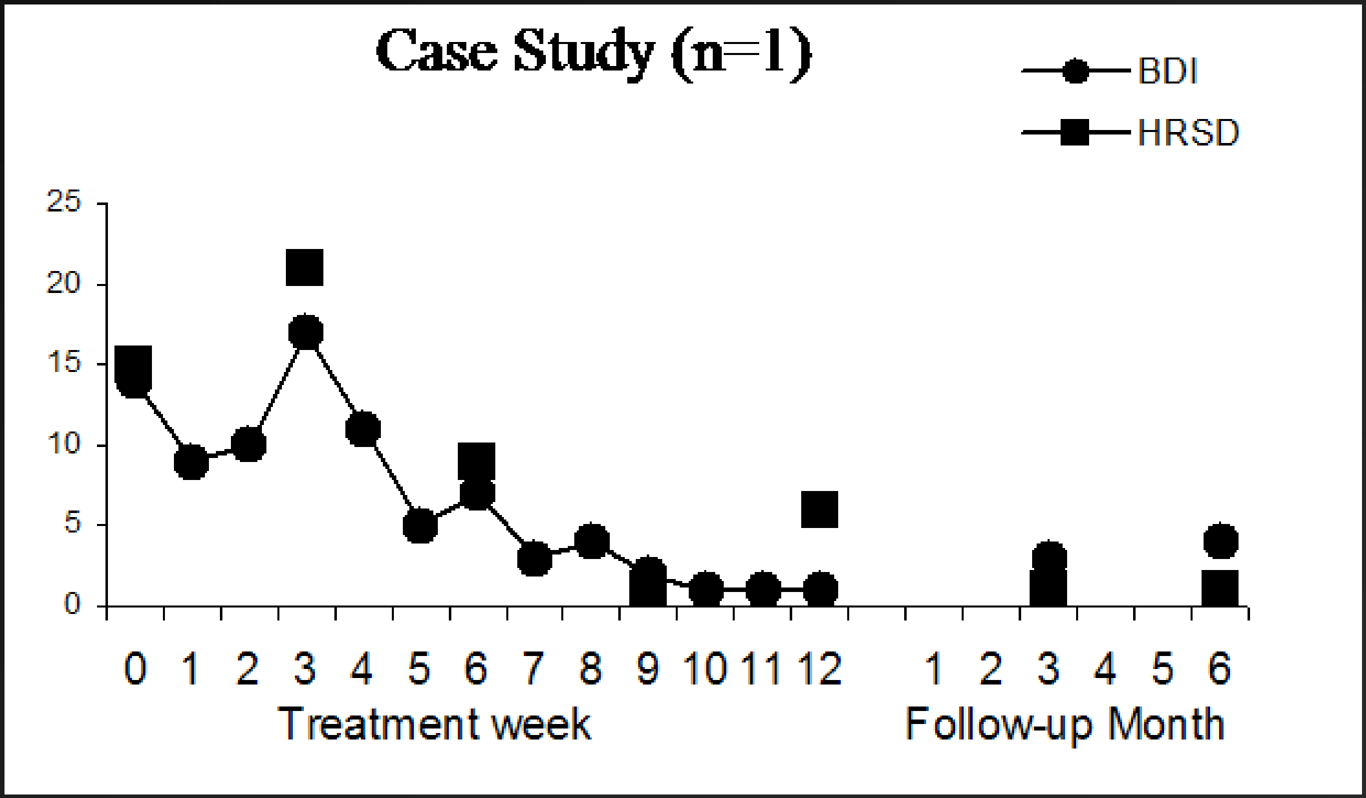


From Allen, Harmon-Jones, and Cavender (2001)

Manipulation of Asymmetry using Biofeedback

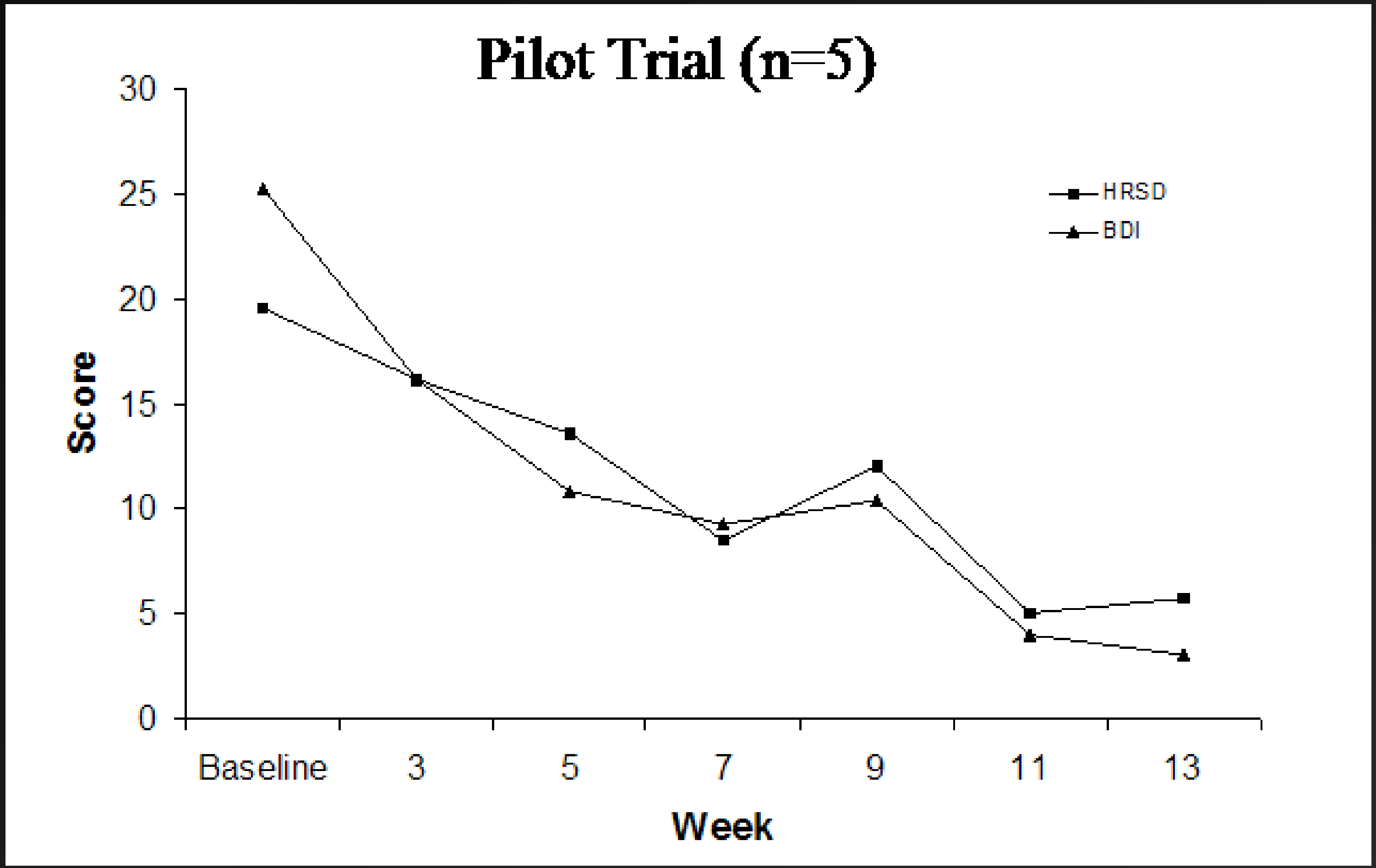
- Phase 1: Demonstrate that manipulation of EEG asymmetry is possible
- Phase 2: Determine whether EEG manipulation has emotion-relevant consequences
- Phase 3: Examine whether EEG manipulation produces clinically meaningful effects
- Phase 4: Conduct efficacy trial

Phase 3a



Biofeedback provided 3 times per week for 12 weeks

Phase 3b



"Open Label" pilot trial, with biofeedback provided 3 times per week for 12 weeks

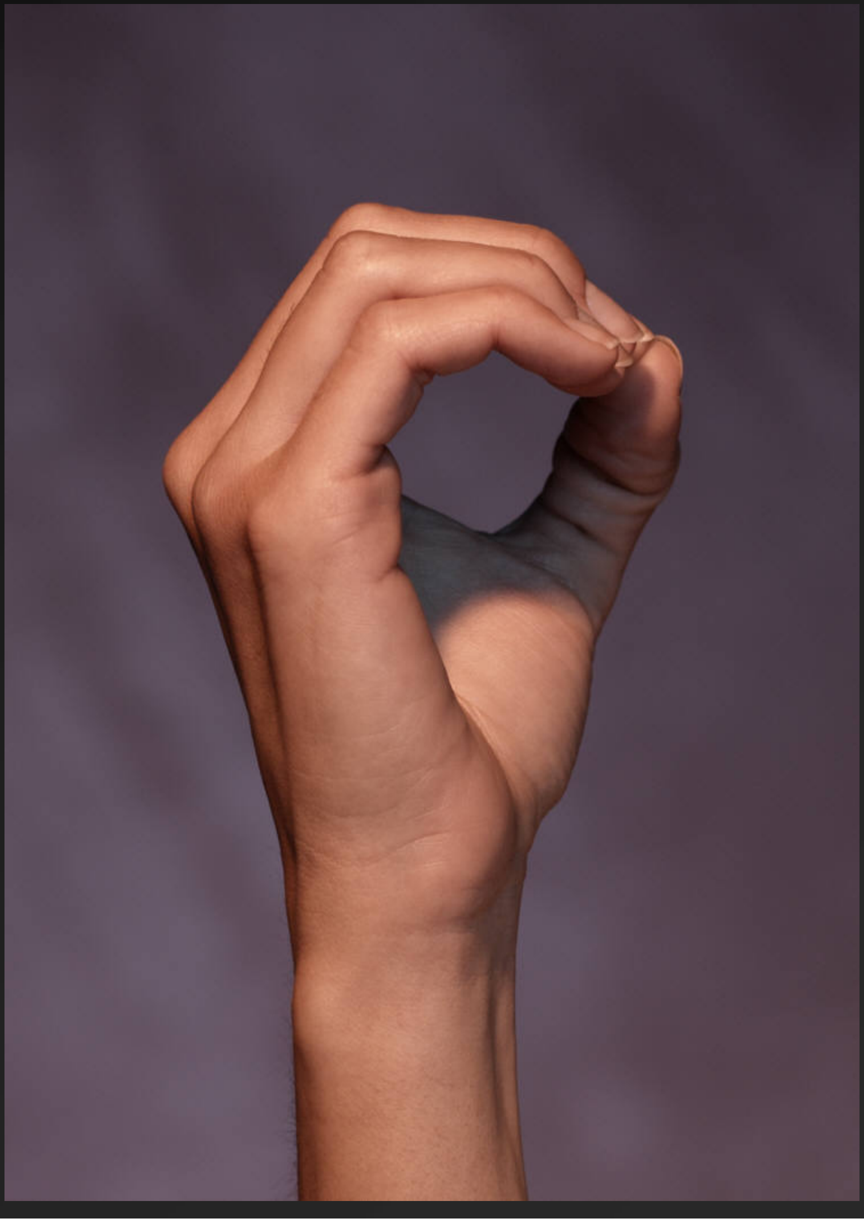
Phase 4: Randomized Control Trial

- Depressed subjects ages 18-60 to be recruited through newspaper ads
- Ad offers treatment for depression but does not mention biofeedback
- Participants meet DSM-IV criteria for Major Depressive Episode (nonchronic)

Design

- Contingent-noncontingent yoked partial crossover design
- Participants randomly assigned to:
    - *Contingent Biofeedback*: tones presented in response to subject's EEG alpha asymmetry
    - *Noncontingent Yoked*: tones presented that another subject had heard, but tones not contingent upon subject's EEG alpha asymmetry
- Treatments 3 times per week for 6 weeks
- After 6 weeks, all subjects receive contingent biofeedback 3 times per week for another 6 weeks

Results



State Changes

- Infants
  - Stanger/Mother paradigm (Fox & Davidson, 1986)
  - Sucrose Vs water (Fox & Davidson, 1988)
  - Films of facial expressions (Jones & Fox, 1992; Davidson & Fox, 1982)
- Primates
  - Benzodiazepines increases LF (Davidson et al., 1992)

State Changes

- Adults
  - Spontaneous facial expressions (Ekman & Davidson, 1993; Ekman et al., 1990; Davidson et al., 1990)
  - Directed facial actions (Coan, Allen, & Harmon-Jones, 2001)

EEG responds to directed facial actions

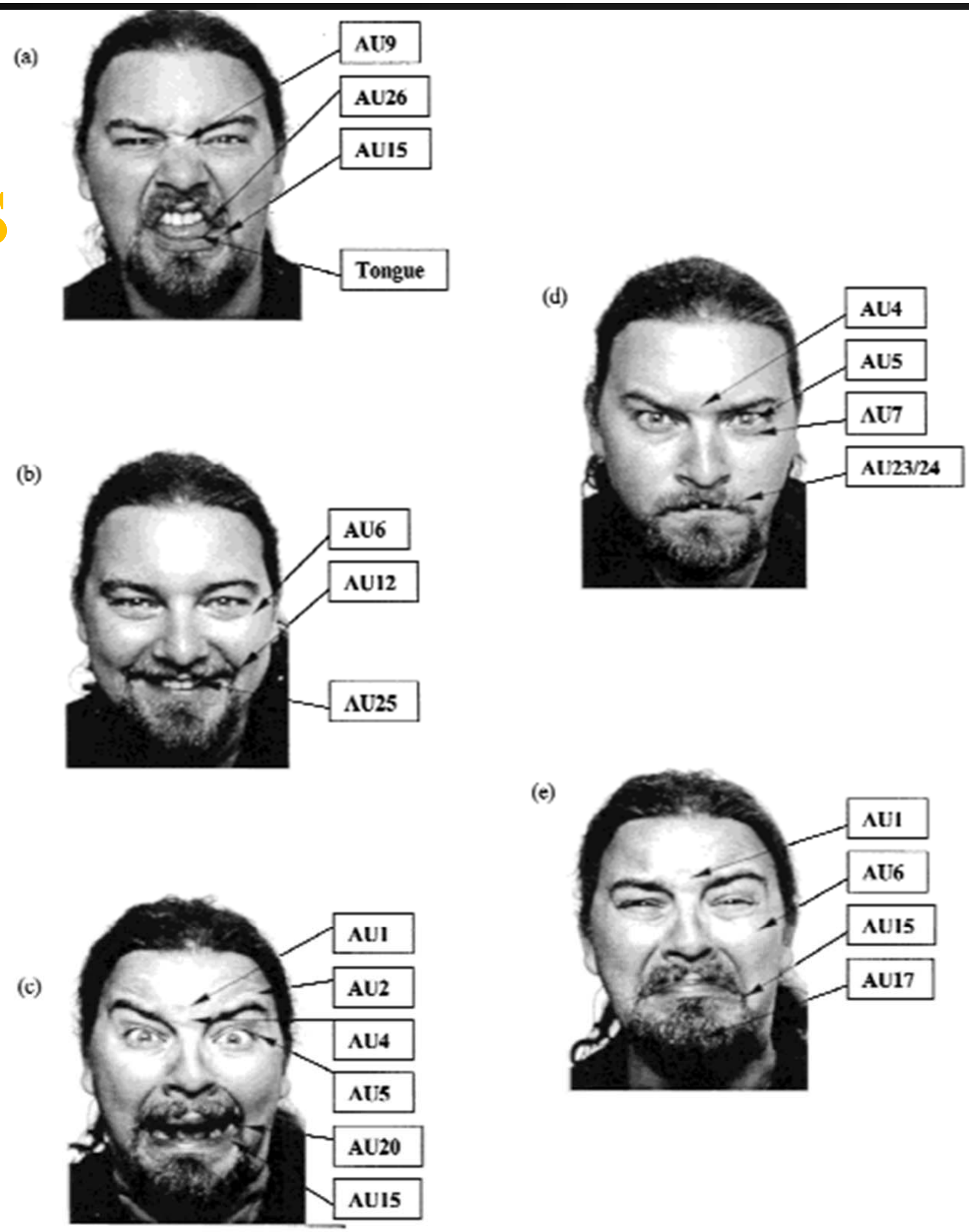
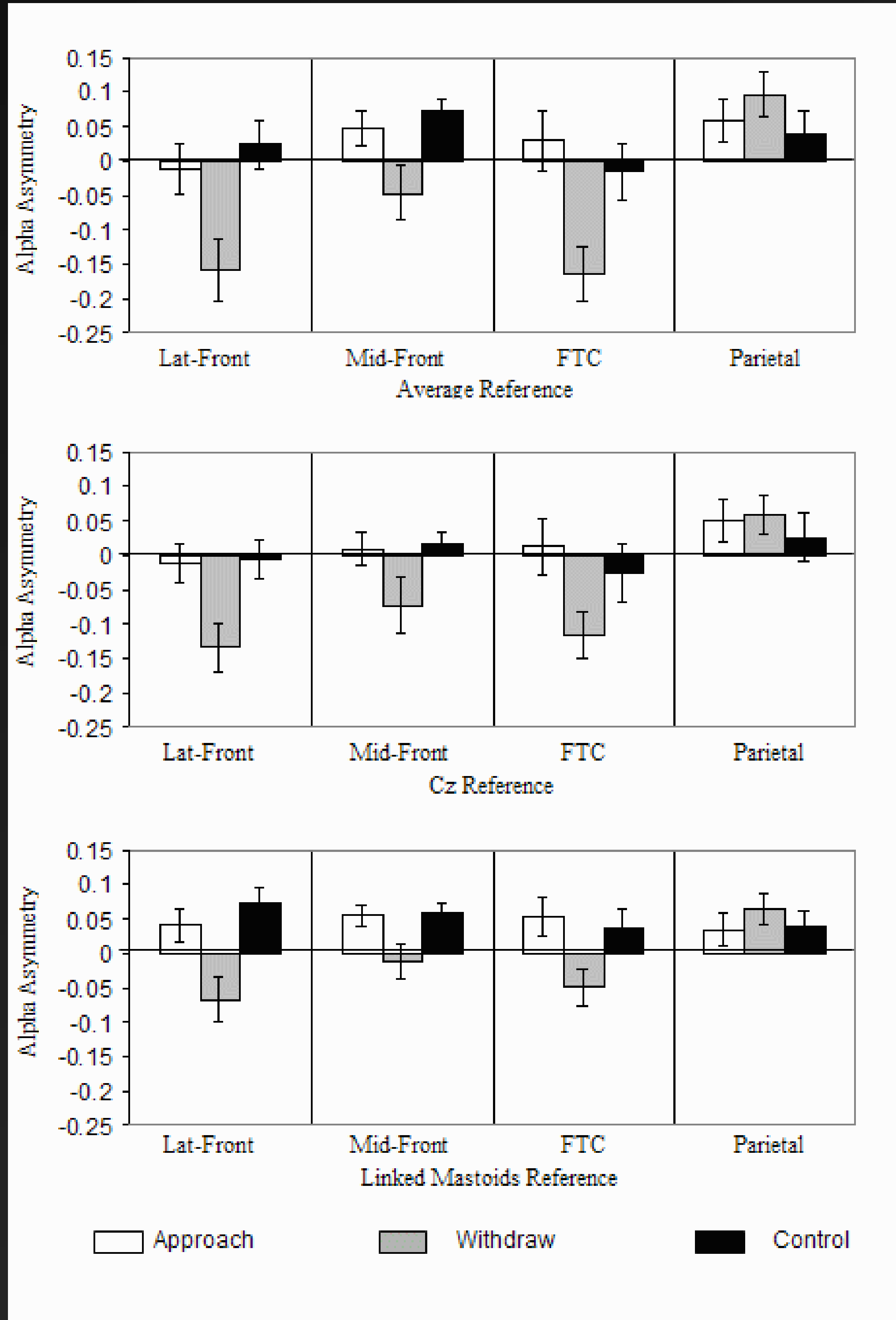


Figure 1. Muscle movements in the full face conditions: (a) disgust, activating AUs 9 (nose wrinkler), 15 (lip corner depressor), 26 (jaw drop), and the "tongue show;" (b) joy, activating AUs 6 (cheek raiser), 12 (lip corner puller), and 25 (lips part); (c) fear, activating AUs 1 (inner brow raiser), 2 (outer brow raiser), 4 (brow lowerer), 5 (upper lid raiser), 15 (lip corner depressor), and 20 (lip stretch); (d) anger, activating AUs 4 (brow lowerer), 5 (upper lid raiser), 7 (lid tightener), 23 (lip tightener), and/or 24 (lip pressor); (e) sadness, activating AUs 1 (inner brow raiser), 6 (cheek raiser), 15 (lip corner depressor), and 17 (chin raiser).

From Coan, Allen, and Harmon-Jones (2001)

EEG responds to directed facial actions



From Coan, Allen, and Harmon-Jones (2001)

States – how short can they be?

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A better estimate of the internal consistency reliability of frontal EEG asymmetry scores

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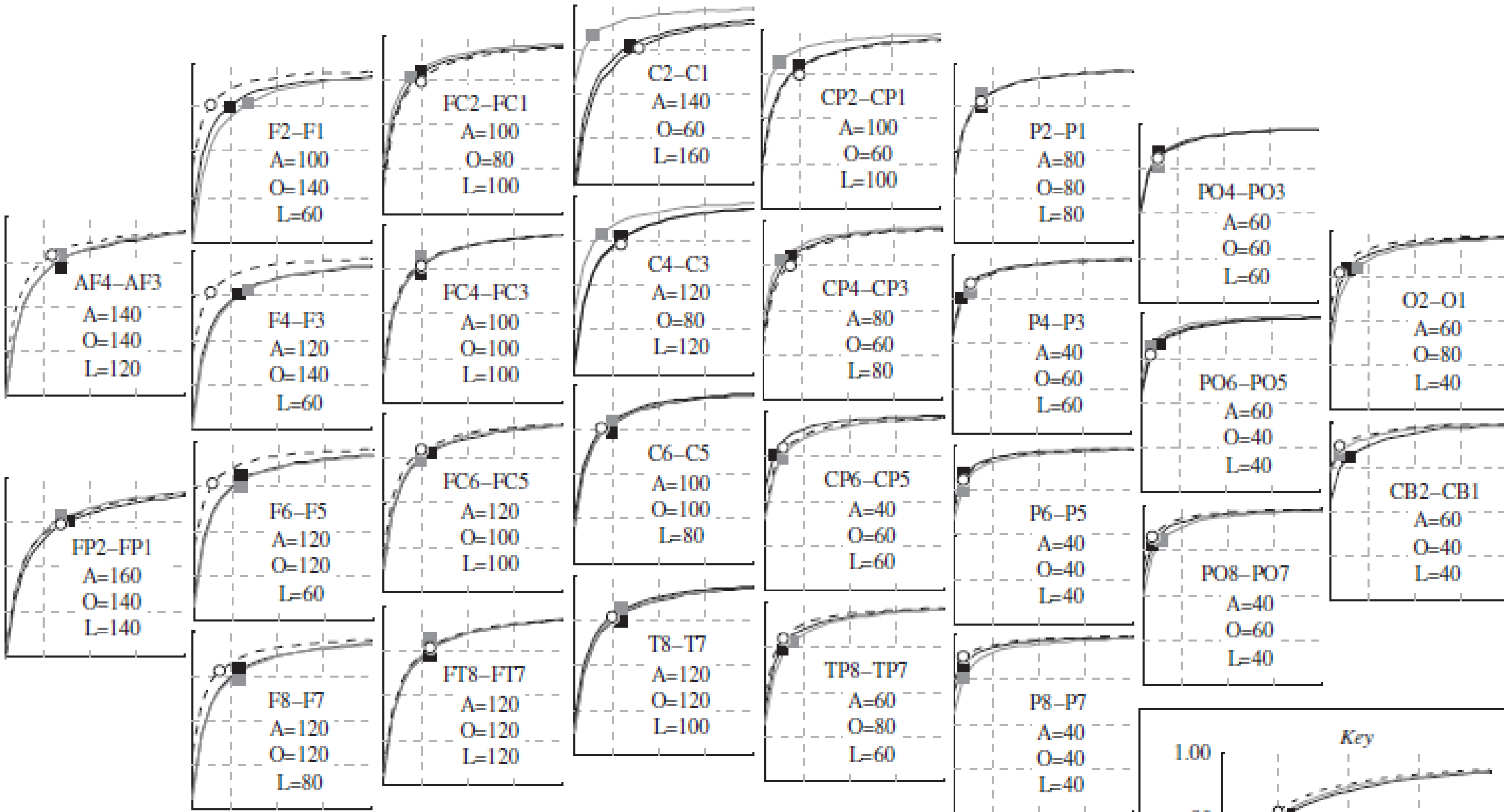
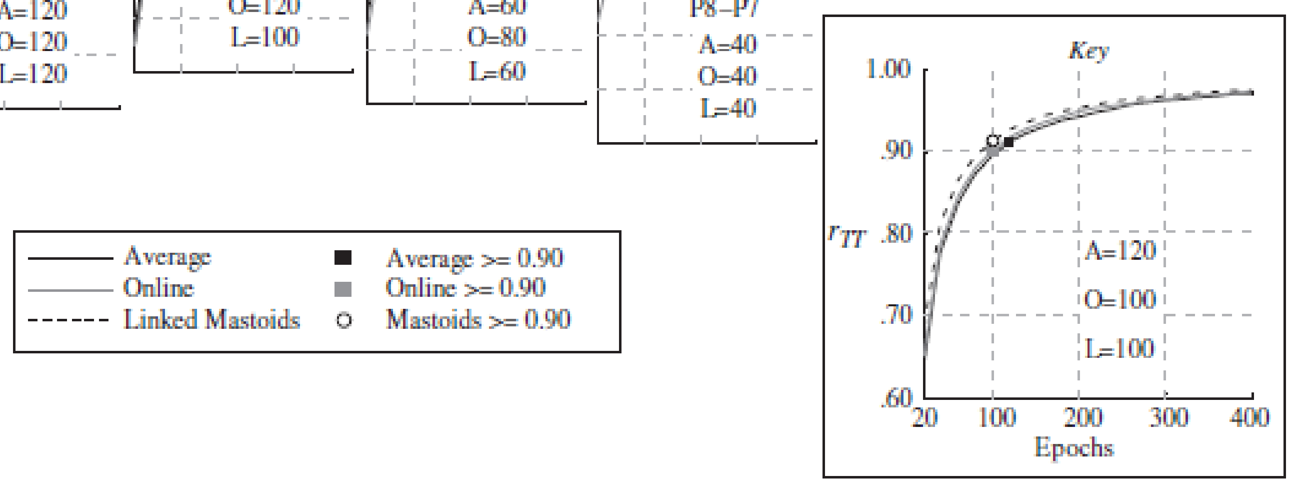
Abstract

Frontal alpha asymmetry is typically computed using alpha power averaged across many overlapping epochs. Previous reports have estimated the internal consistency reliability of asymmetry by dividing resting EEG sessions into segments of equal duration (e.g., 1 min) and treating asymmetry scores for each segment as "items" to estimate internal consistency reliability using Cronbach's alpha. Cronbach's alpha partly depends on the number of items, such that this approach may underestimate reliability by using less than the number of distinct items available. Reliability estimates for resting EEG data in the present study (204 subjects, 8 sessions) were obtained using mean split-half correlations with epoch alpha power as treated as separate items. Estimates at all scalp sites and reference schemes approached .90 with as few as 100 epochs, suggesting the internal consistency of frontal asymmetry is greater than that previously reported.





Notes:

- Split Half
- 1000 Iterations
- Mean Fisher Z
- Spearman-Brown

Figure 1. Estimated internal consistency reliability (r_{TT}) of asymmetry scores for epoch set sizes n ranging from 20 to 400, across average (black), online (gray), and linked-mastoids (dashed) reference derivations and all homologous electrode pairs. Graph markers and table insets indicate the epoch set size n at which the estimated internal consistency reliability coefficient for each reference derivation was greater than or equal to .90.

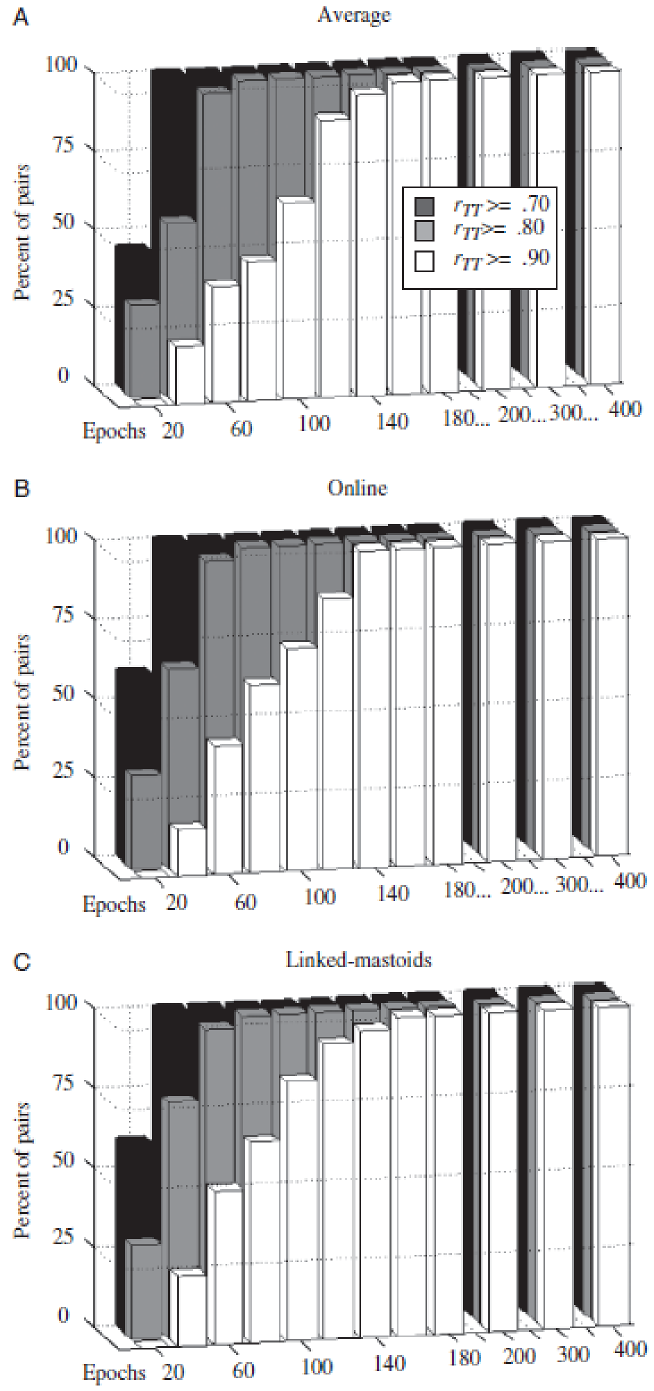


Figure 2. Percentage of homologous electrode pairs in which estimates of internal consistency reliability (r_{TT}) of asymmetry scores were greater than or equal to .70 (white), .80 (light gray), and .90 (dark gray) as a function of epoch set size n and reference derivation.

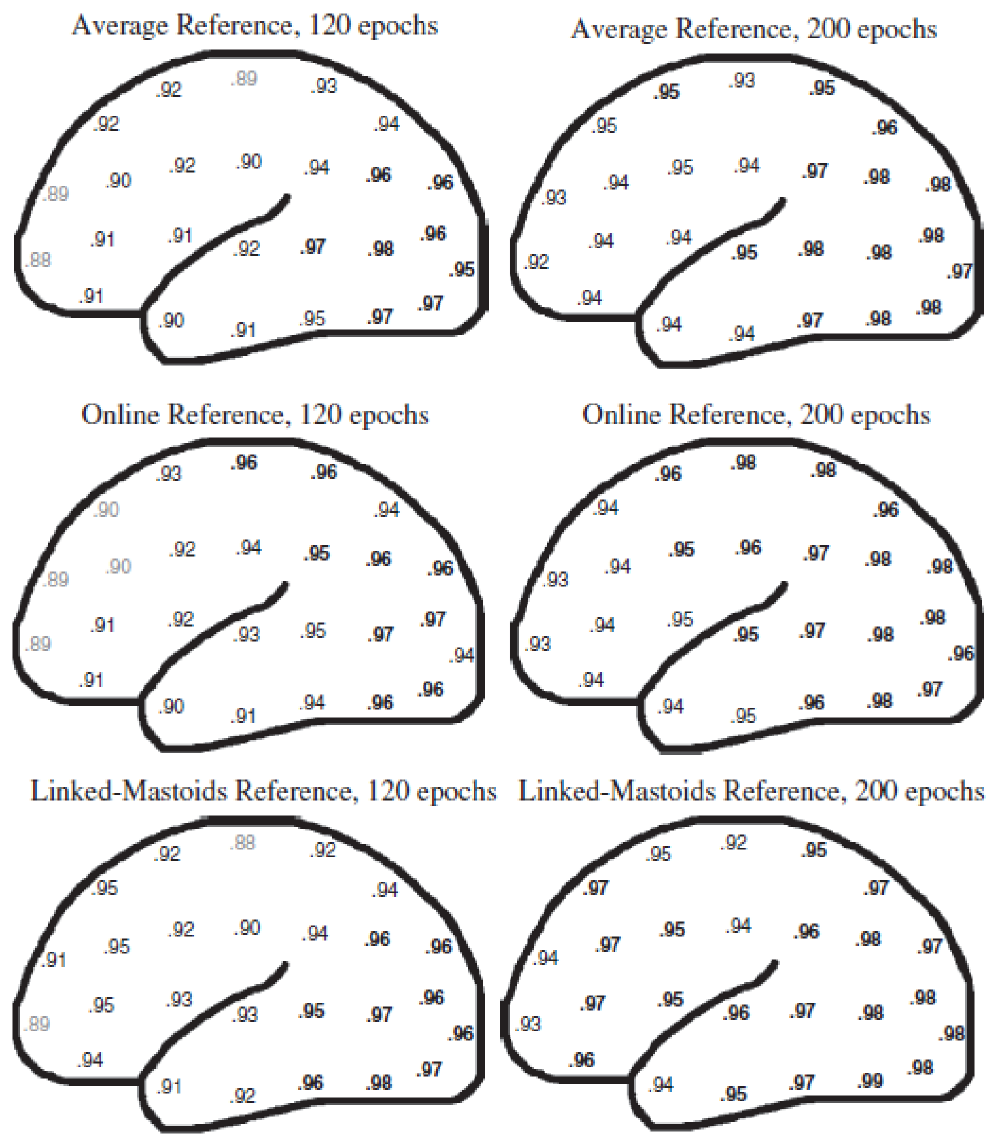


Figure 3. Estimated internal consistency reliability (r_{TT}) of asymmetry scores for epoch set sizes of 120 and 200, with light gray numbers indicating $.85 \leq r_{TT} < .90$ and bold numbers indicating $r_{TT} \geq .95$ (the pair CB2–CB1 was omitted).