Technical Foundations of Neurofeedback

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Introduction

- Electrophysiology
- Instrumentation
- Computerization
- Signal Processing
- User Interfacing
- System Overview

Neurofeedback

Neurofeedback is a form of biofeedback training that uses the EEG (Electroencephalogram), also known as the "brain wave" as the signal used to control feedback. Sensors applied to the trainee's scalp record the brainwaves, which are converted into feedback signals by a human/machine interface using a computer and software. By using visual, sound, or tactile feedback to produce operant conditioning of the brain, it can be used to induce brain relaxation through increasing alpha waves. A variety of additional benefits, derived from the improved ability of the CNS (central nervous system) to relax, may also be obtained.

Neurofeedback Mechanisms

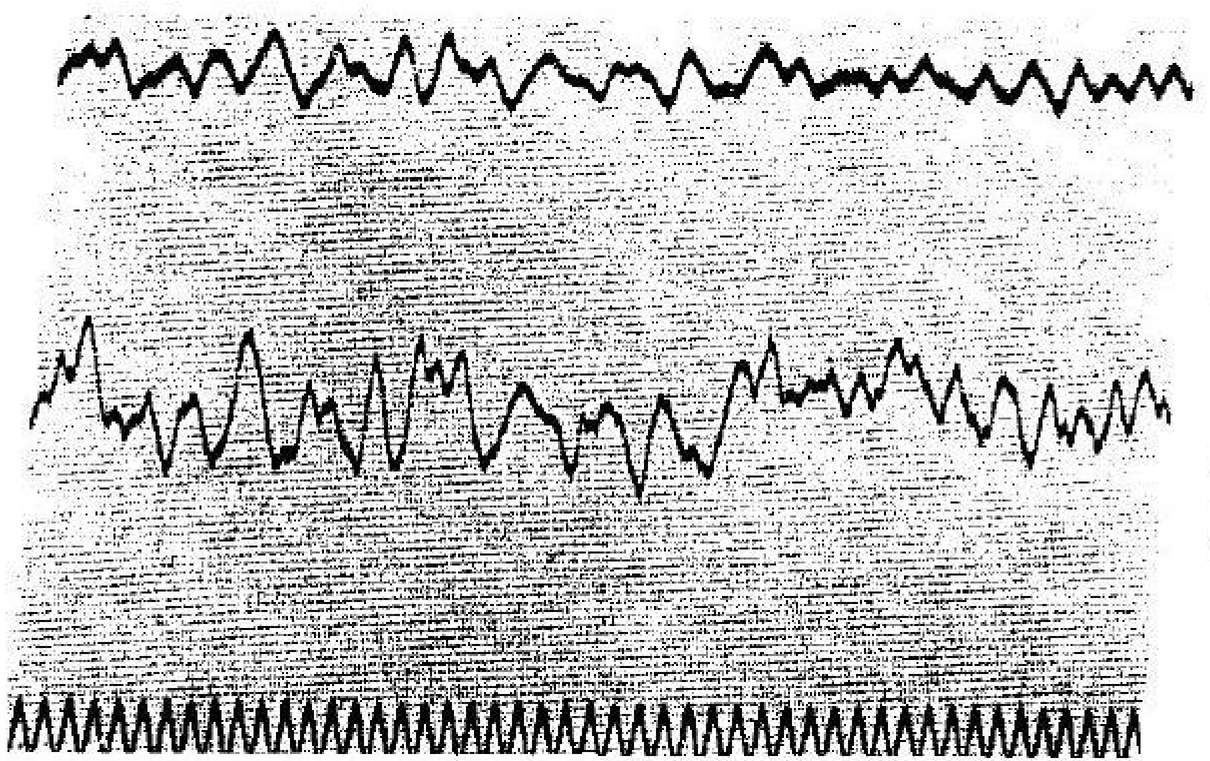
- Operant ("Instrumental") Conditioning
  – Learning to perform a task to get a reward
- Classical ("Pavlovian") Conditioning
  – Learning to connect previously unpaired events
- Concurrent Learning
  – Derived from experiencing simultaneous processes
- Self Efficacy
  – Resulting from self-empowerment and self-awareness

Neurofeedback Mechanisms

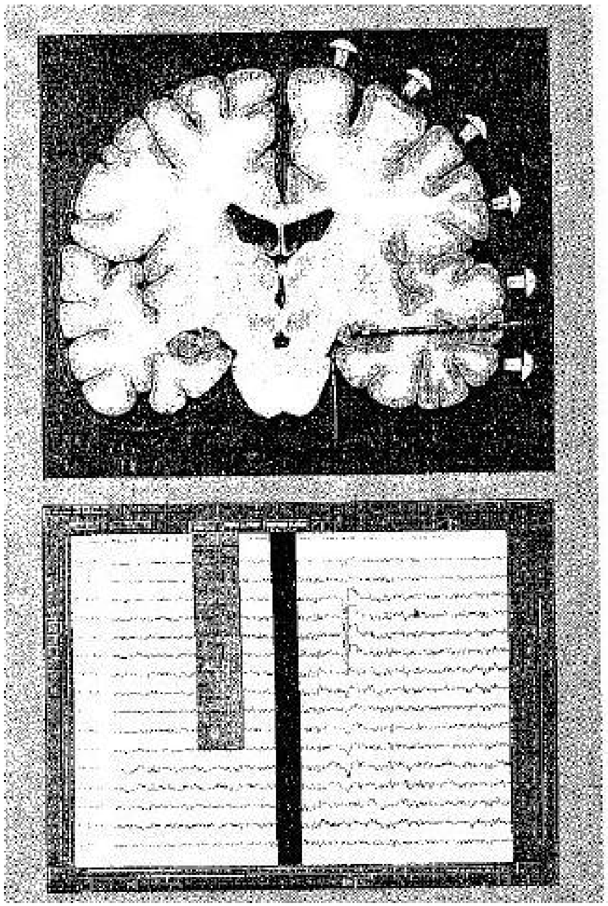
- What is the “operant”?
  - EEG brain rhythm or patterns
- What is the reward?
  - Visual or auditory feedback, scoring
- What is the goal?
  - Brain learns flexibility, awareness, choice
  - Operates at the neuronal level
- Why does it work?
  - Brain seeks novelty, aesthetic, achievement
  - Brain is capable of learning self-regulation

First Human EEG Studies - 1924

Hans Berger - 1932



1988 - 1996

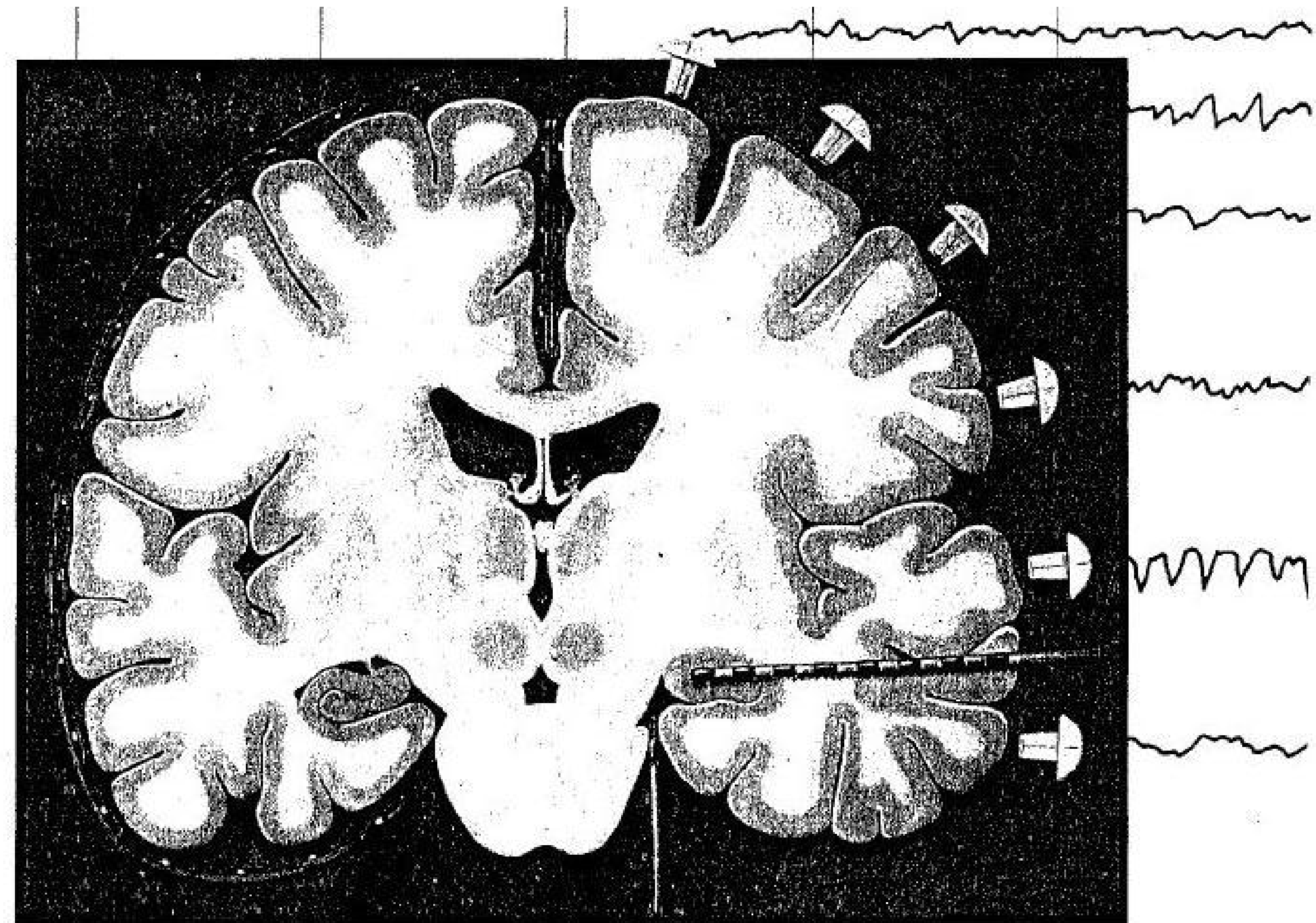


The Epilog System

Automated Long-Term EEG Monitoring for Epilepsy

Thomas F. Collura, Ernest C. Jacobs,
Richard C. Burgess, and John P. Turnbull
Cleveland Clinic Foundation

Brain Source Localization



Electrophysiology

- Neuronal Potentials – dipoles generation by single cells
- Population Dynamics – synchrony reinforces single strength of signal
- Brain Physiology & anatomy defines electrical generators
- Volume Conduction to scalp through cerebral fluid and tissue
- Skin Interface to sensors

Poisson's Equation

The forward problem can be stated as follows: given known charge distributions and volume conductor geometries and properties, predict the resulting surface potential distribution. The solution involves applying numerical or analytical methods, for any known set of geometries and boundary conditions,[55,64] to solve Poisson's equation:

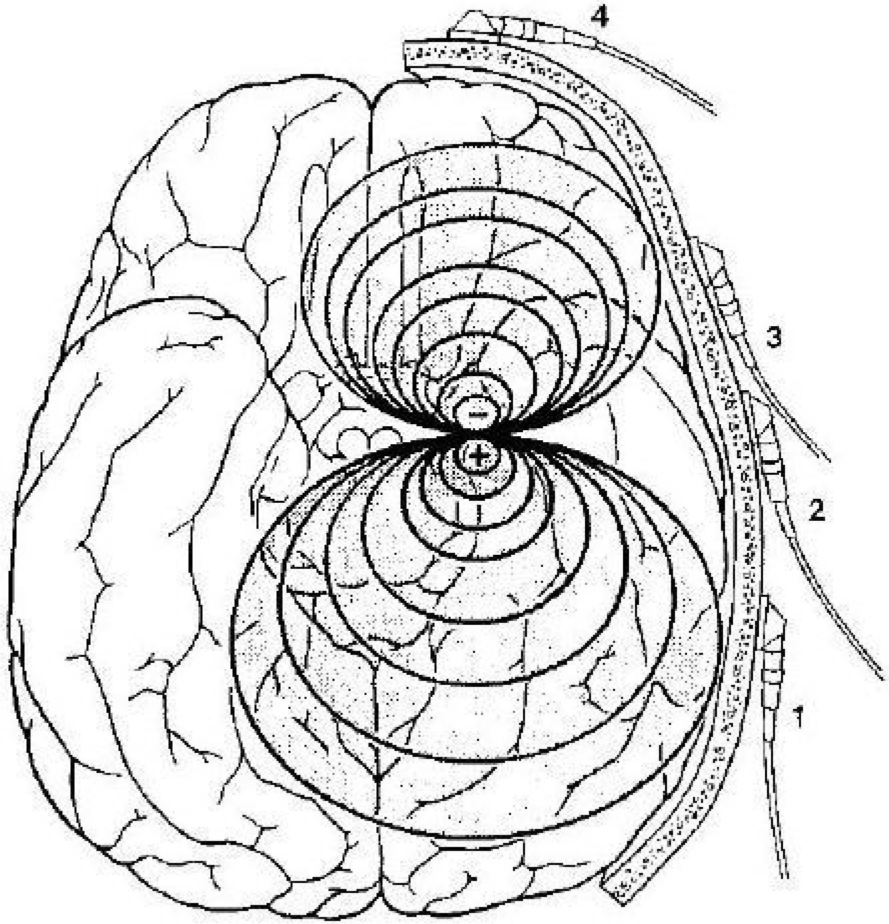
$$\nabla^2 \phi = -\rho/\epsilon$$

where ∇^2 is the second spatial gradiant operator, ϕ is the scalar potential in volts, ρ is the free charge density, and ϵ is the permittivity of the mass of tissue. Multiple sources can be shown to combine linearly, so that a combination of sources results in the arithmetic sum of the potential distributions that each would produce individually.

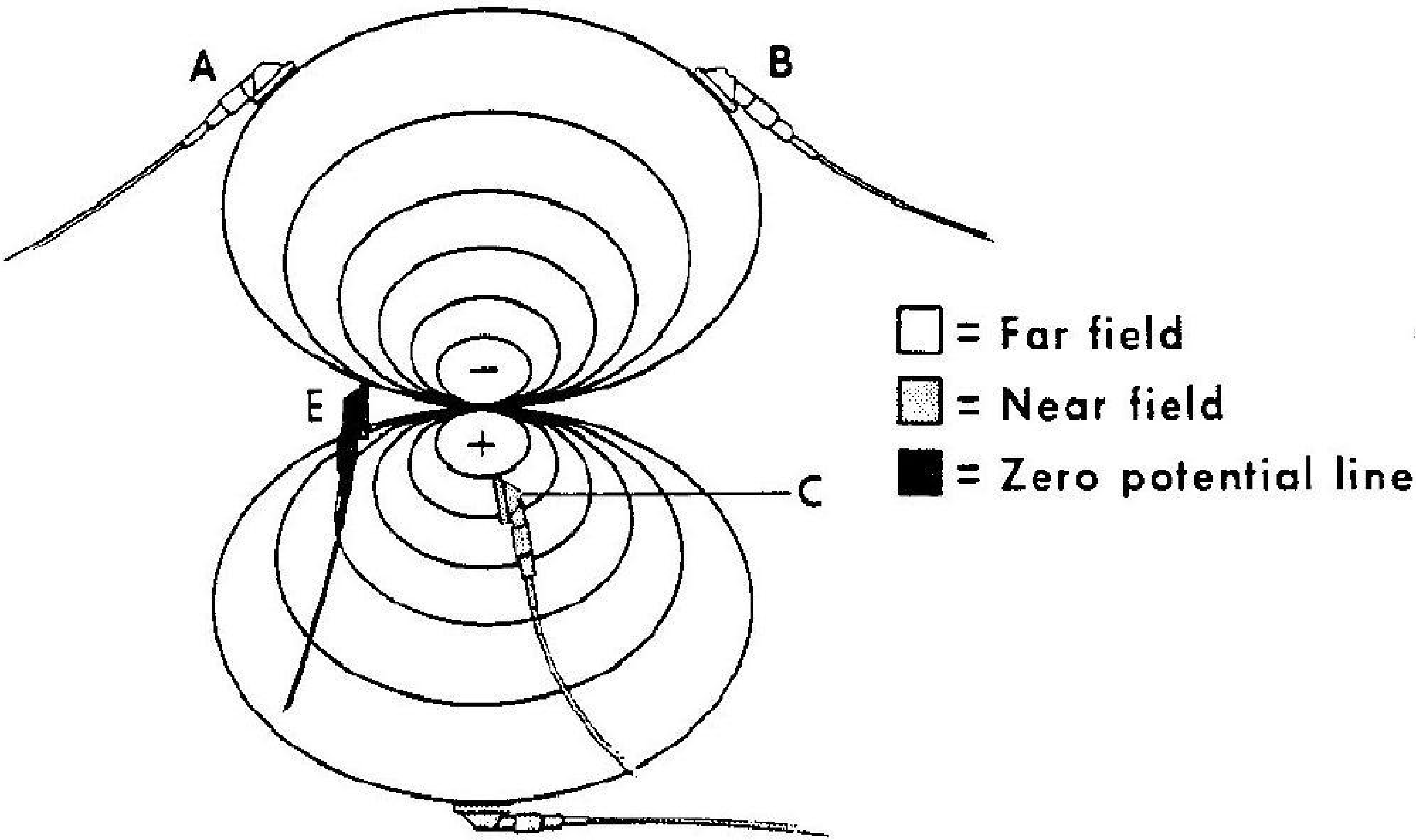
Dipole Generation

- Brain Cells polarize to produce + and – sides
- Each cell is a tiny "battery"
- Dipoles have magnitude and orientation
- Dipoles cause current to flow in brain fluid and tissue
- Multiple dipoles reinforce to produce larger signal
- Pyramidal cells in cortical layers 2-5 are primary generators of scalp potential
- axis

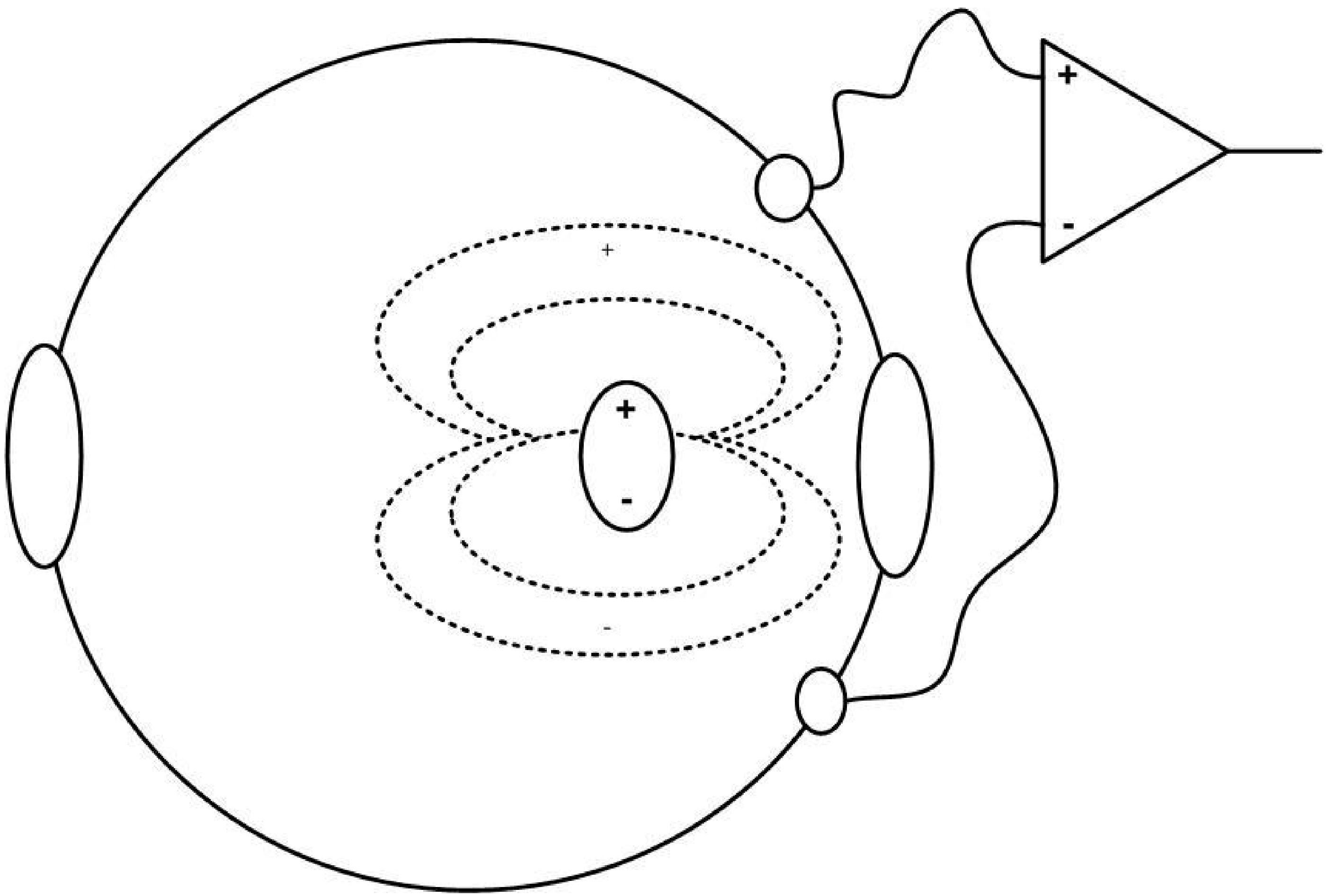
Realistic Head Dipole Source



Dipole Field Measurement



Sample EEG Computation



Dipoles - summary

- All brain dipoles have:
  - **Location – can “move”**
  - **Magnitude – can oscillate and vary in size**
  - **Orientation – can change as sources move among sulci and gyri**

EEG Current Flow

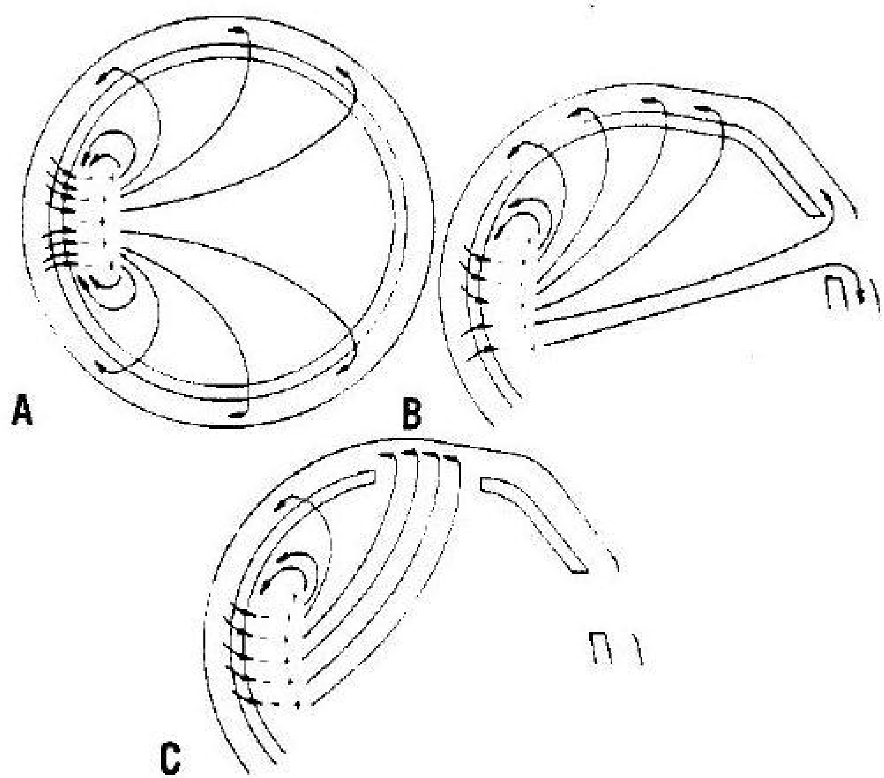
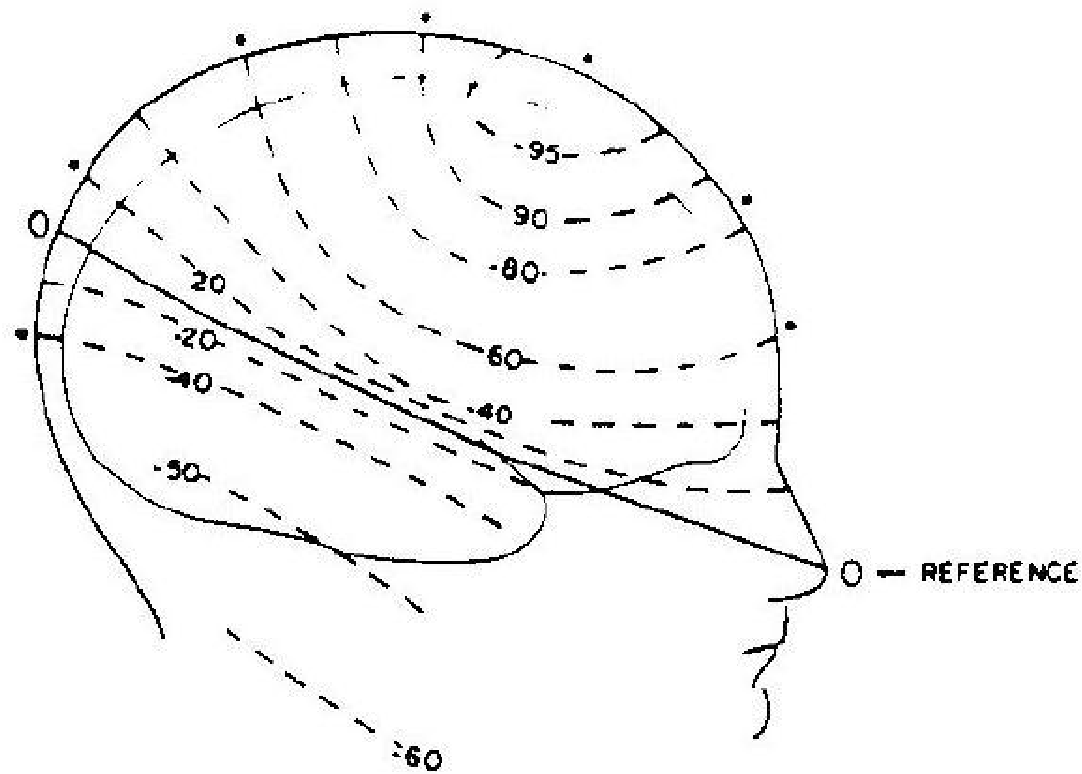
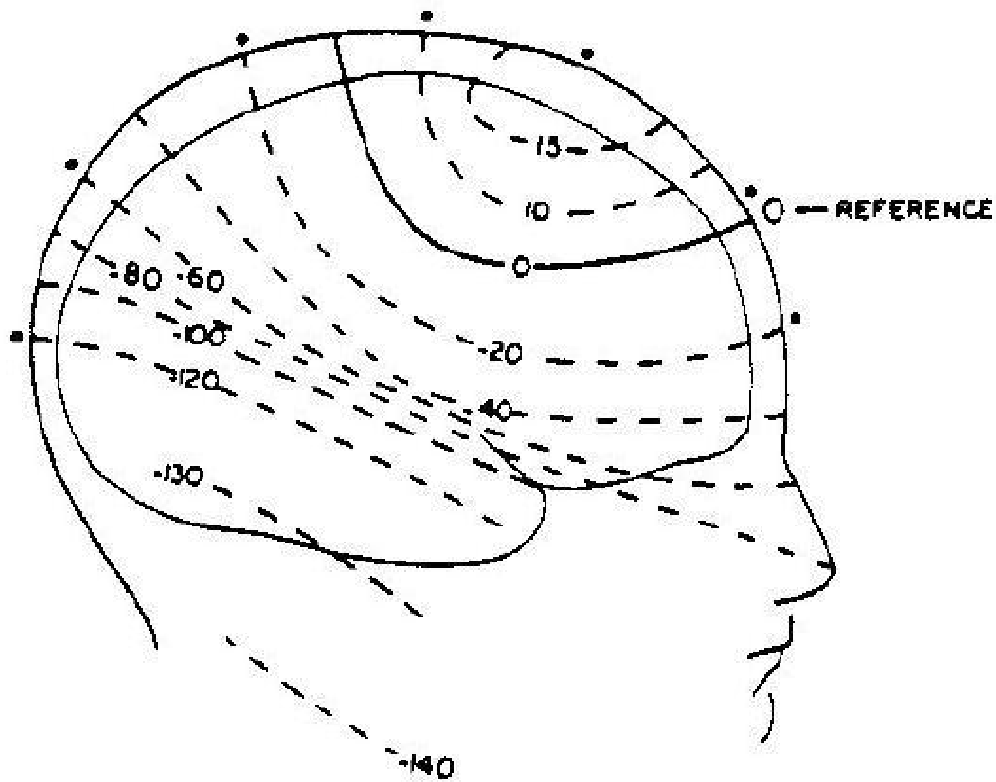


Fig. 16–1. Current flow as a result of a putative dipole layer generator in the occipital cortex. In the spherical head model shown in **A**, the current flow is relatively uniformly distributed. In **B**, a nonspherical head model with orbital openings, and **C**, a nonspherical head model with a surgically induced opening, the current follows the pathways of least resistance. From Nunez,[55] with permission.

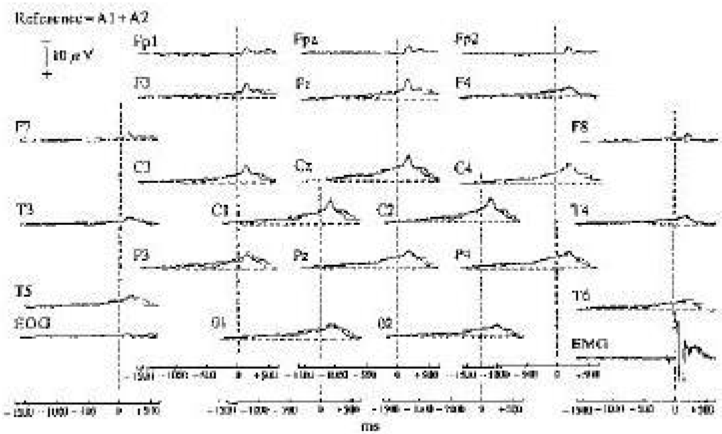
Effect of EEG "blurring"

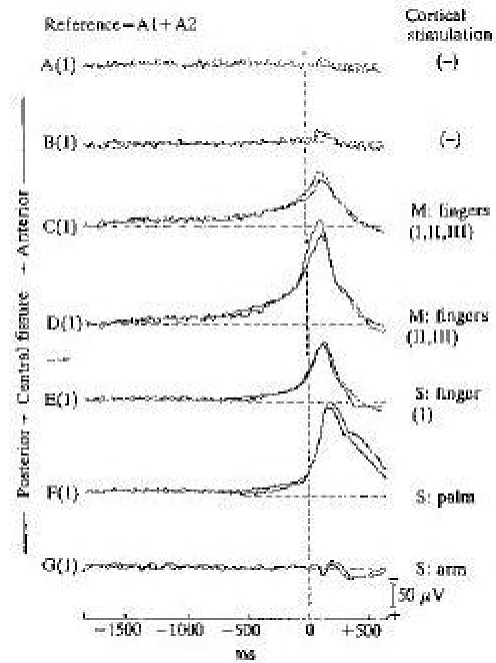


Effect of Reference Placement

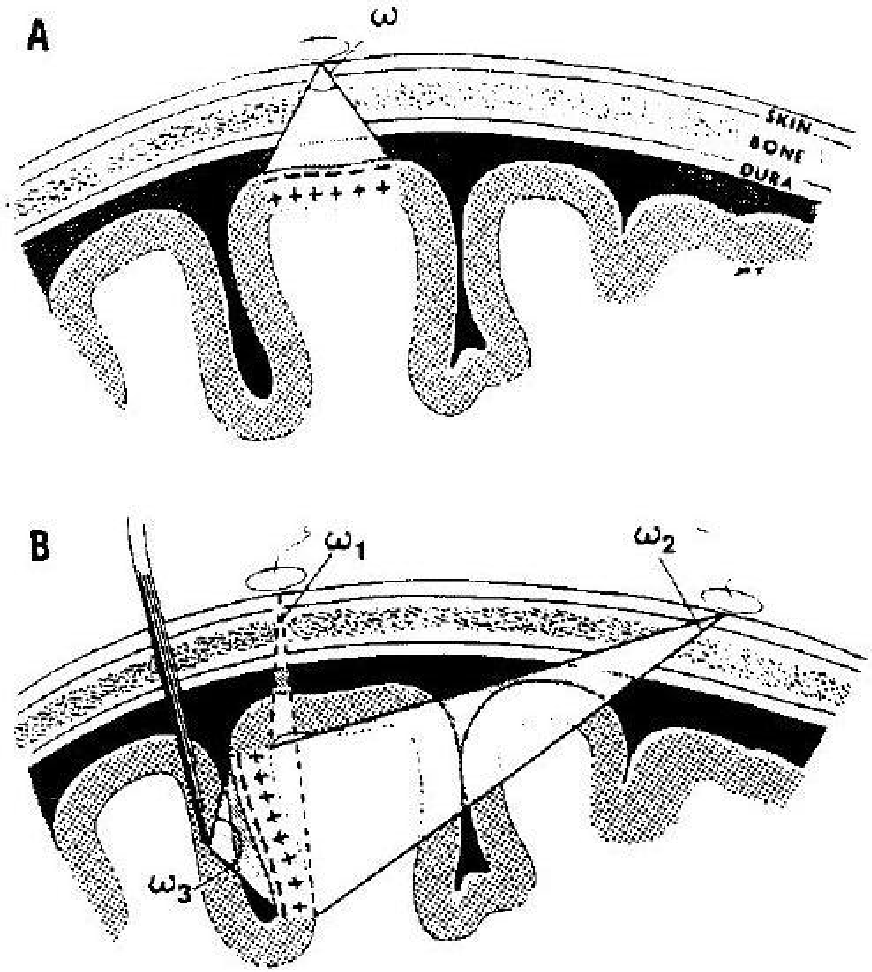


Scalp EEG vs. Invasive EEG (1 cm spacing)

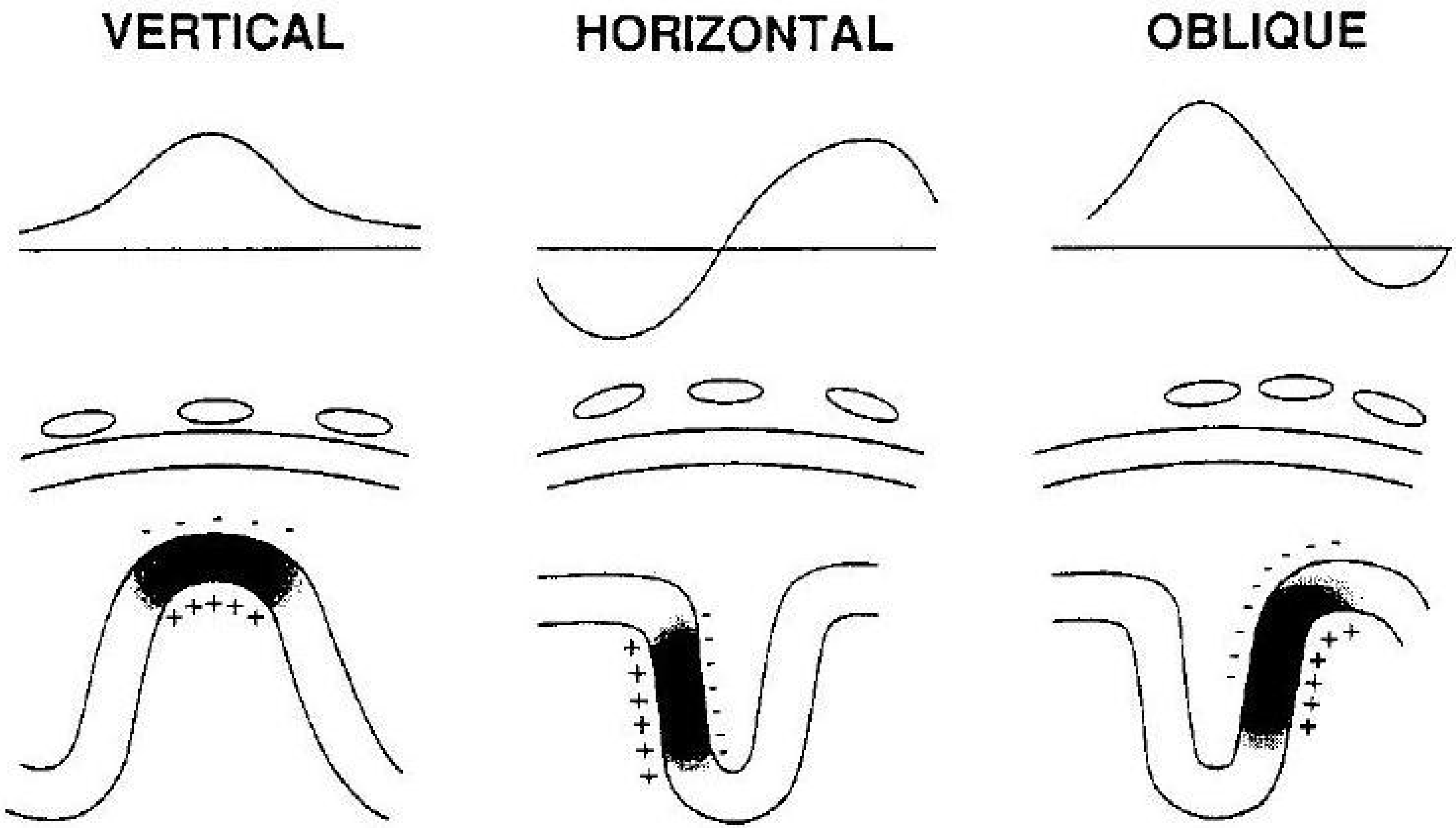




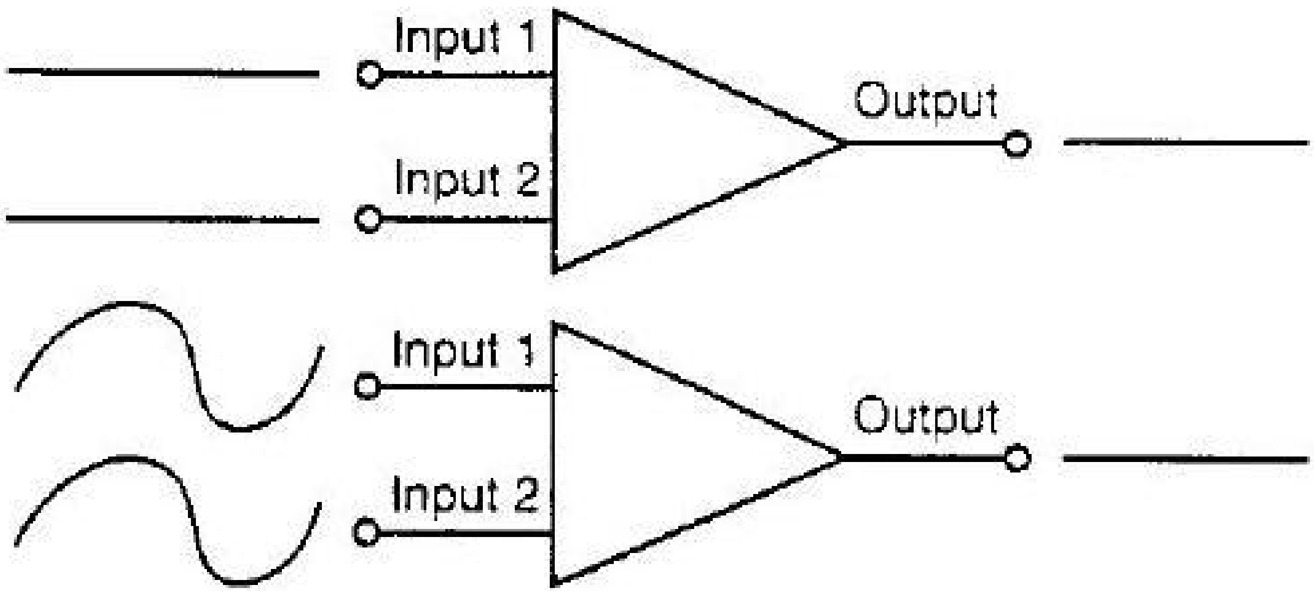
Paradoxical Lateralization



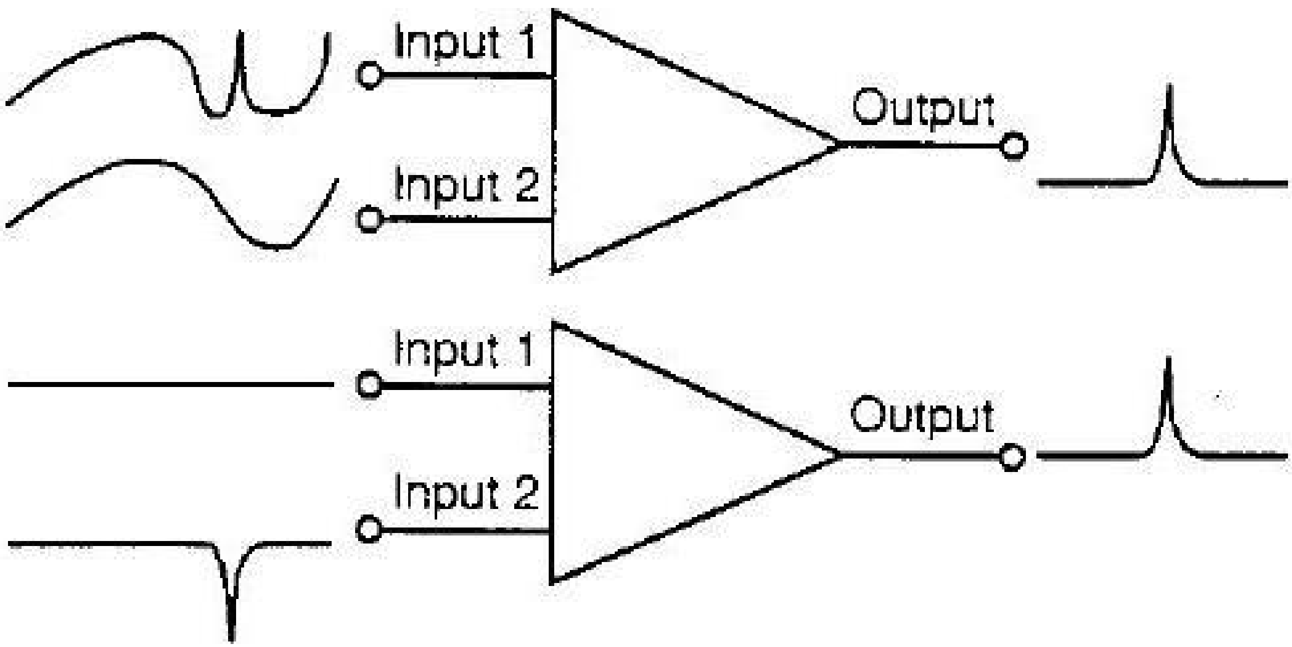
Oblique EEG Generators



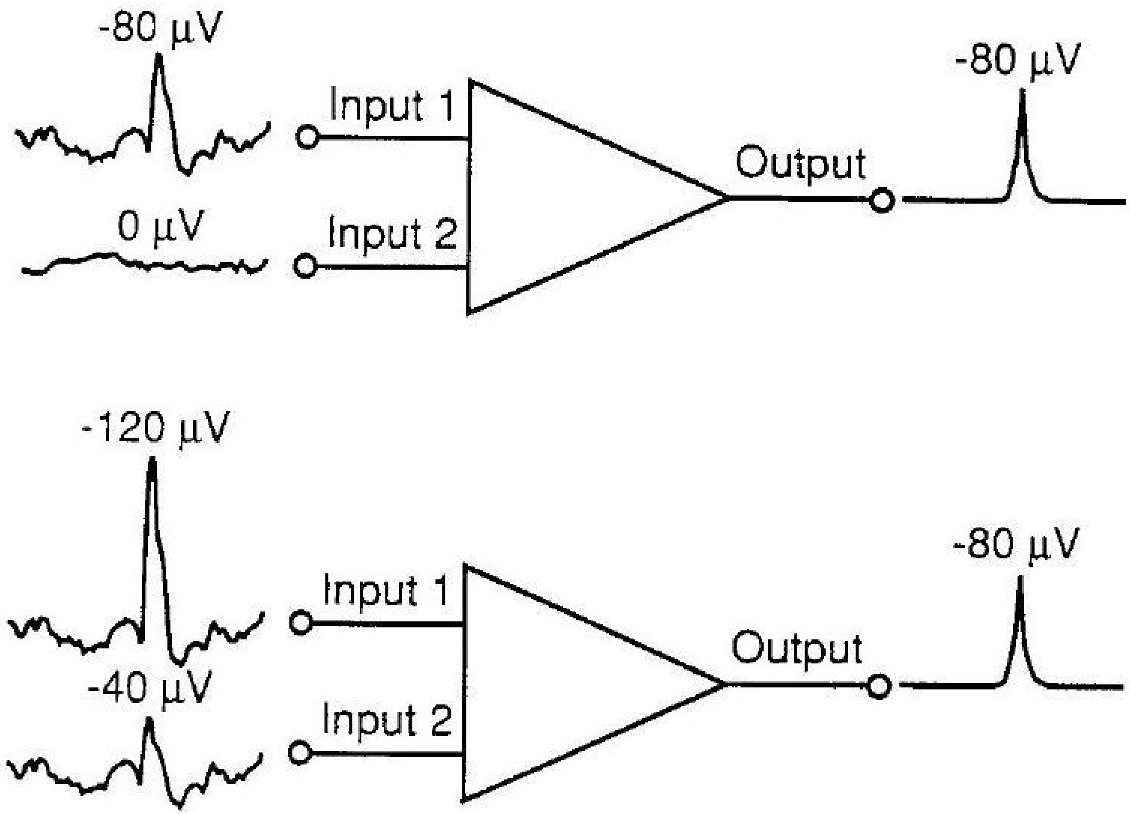
Differential Amplifier – "zero" output



Differential Amplifier – nonzero output



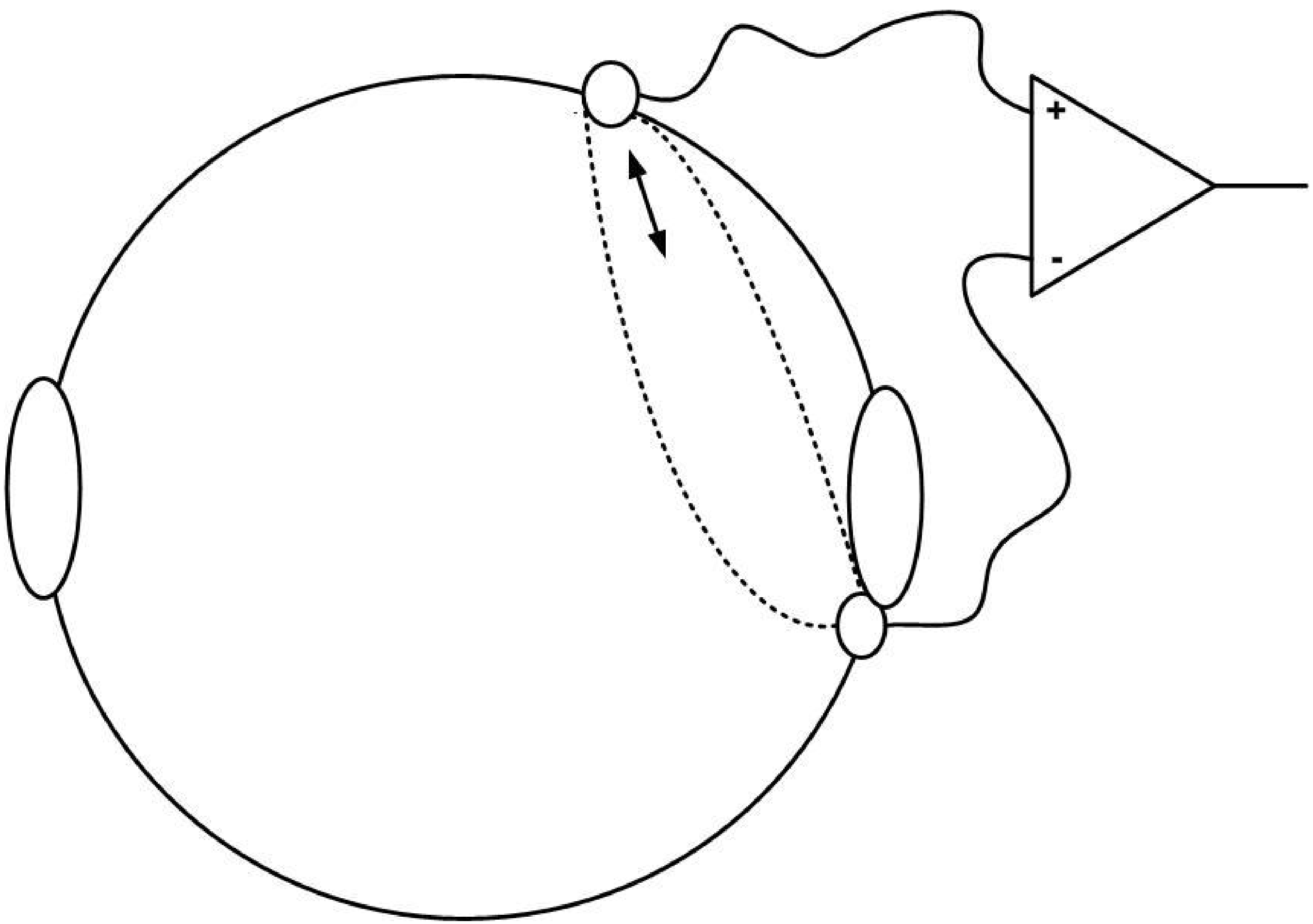
Differential Amplifier – nonzero output



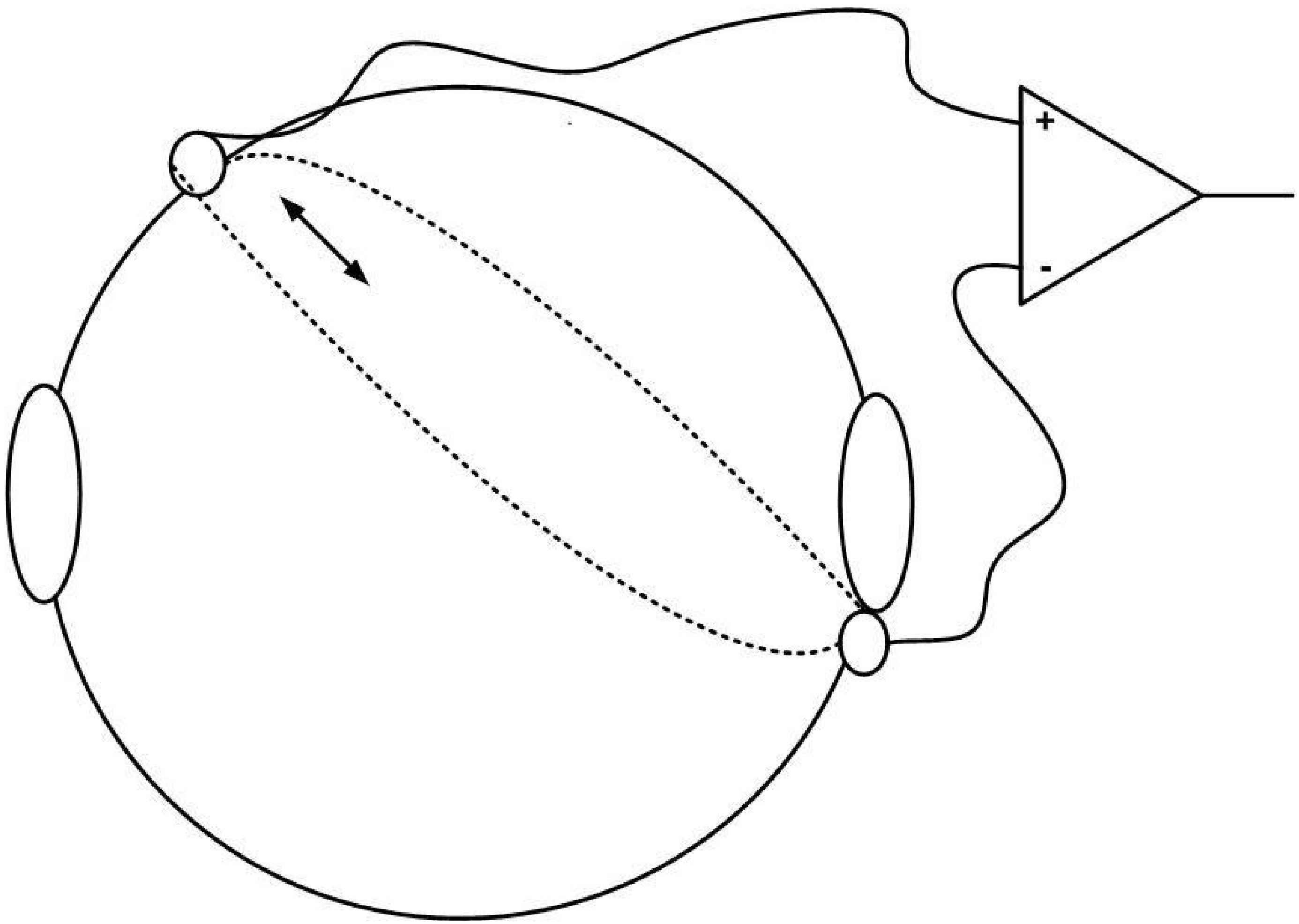
Dipole Sensing

- Sensor pair with differential amplifier picks up:
  - Sources near either sensor
  - Sources between both sensors
  - Sources aligned parallel to sensor axis

Region of Maximum Sensitivity



Contralateral Reference



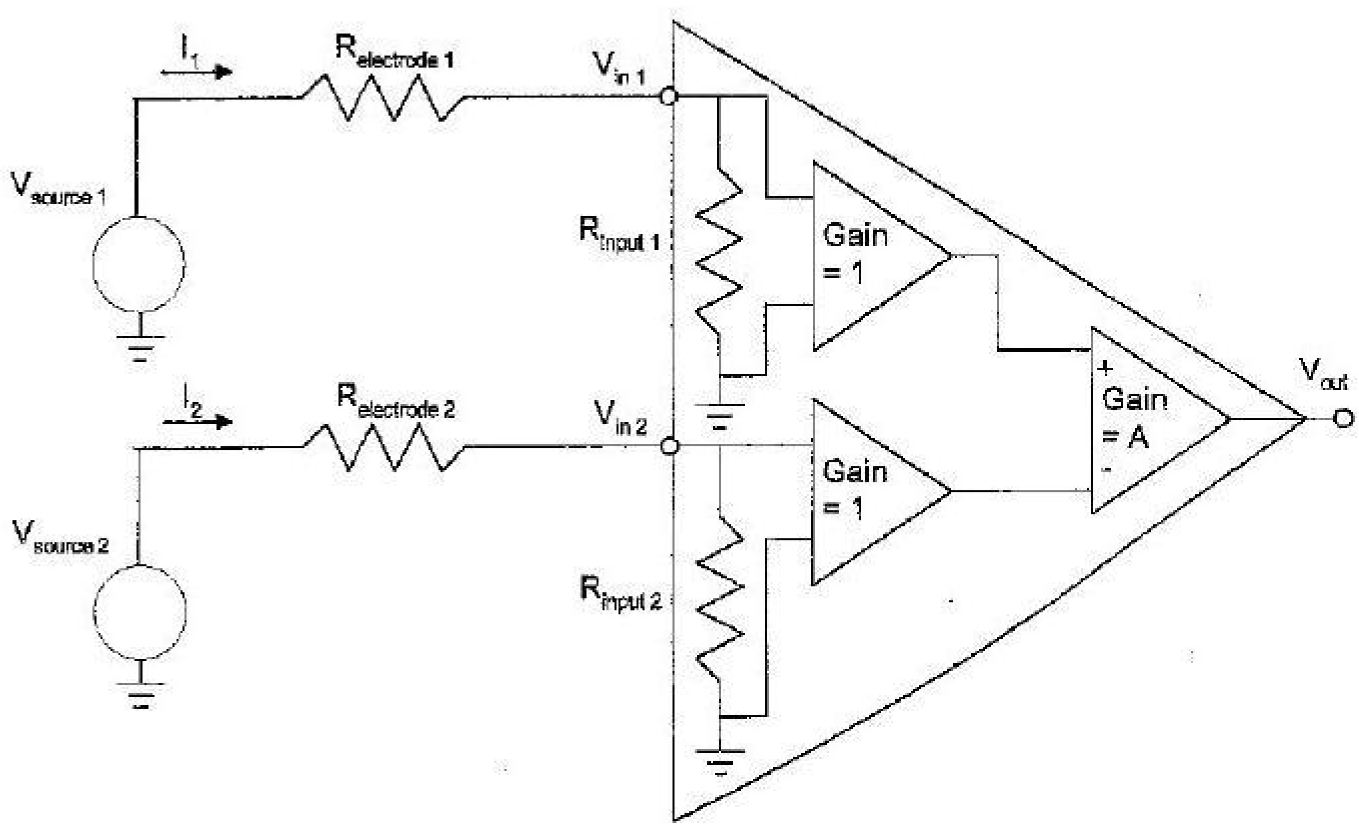
EEG Electrophysiology

- "Forward problem" – given sources and anatomy, predict surface potentials
  - Solved & deterministic – 1 solution exists for any set of sources and anatomy
- "Inverse problem" given surface potentials, find sources and anatomy
  - Non-deterministic - many solutions exist for any surface potential distribution

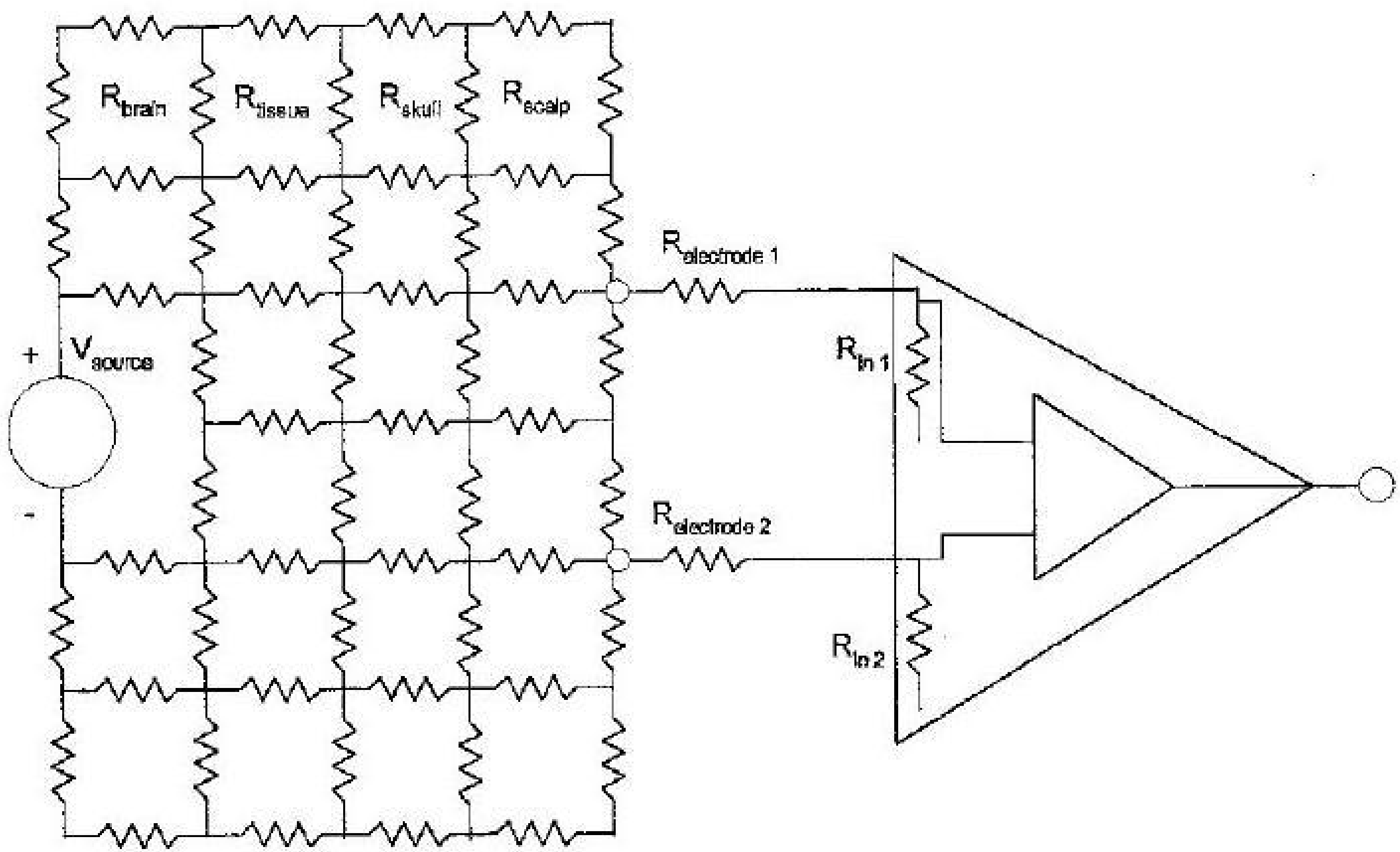
EEG Amplification

- Picks up difference between active & reference via. subtraction
- CMRR – common-mode rejection ratio measures quality of subtraction
- High CMRR rejects 60 Hz, other common-mode signals, amplifies difference
- Sensor pair picks up dipoles near sensors, between sensors, and parallel to sensor

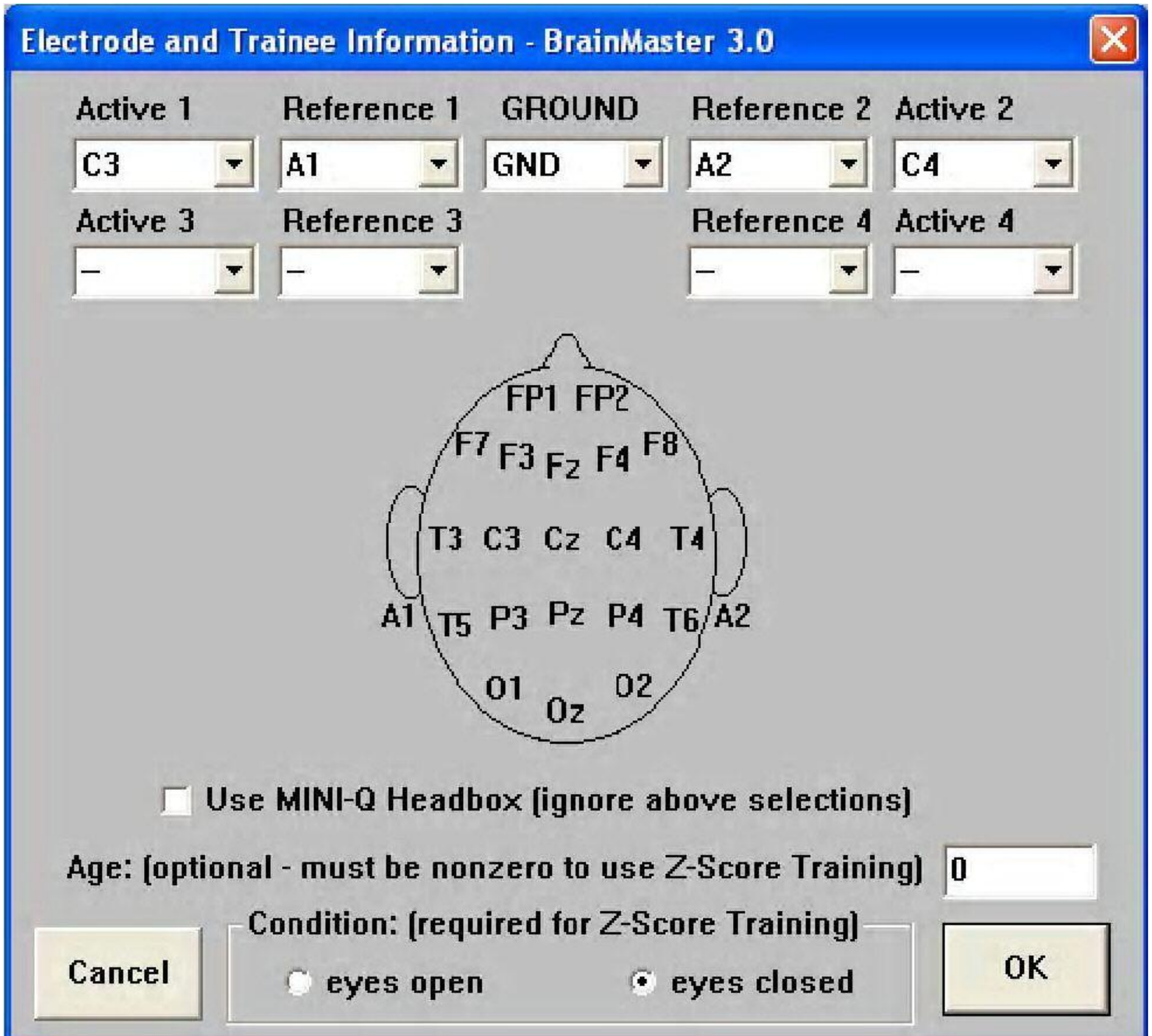
Model for Differential Amplifier



Model for Differential Amplifier & EEG Generators



10-20 system


Electrode and Trainee Information - BrainMaster 3.0
Active 1
Reference 1
GROUND
Reference 2
Active 2
C3
A1
GND
A2
C4
Active 3
Reference 3
Reference 4
Active 4
FP1 FP2
F7 F3 Fz F4 F8
T3 C3 Cz C4 T4
A1 T5 P3 Pz P4 T6 A2
O1 Oz O2
Use MINI-Q Headbox (ignore above selections)
Age: (optional - must be nonzero to use Z-Score Training)
0
Condition: (required for Z-Score Training)
eyes open
eyes closed
Cancel
OK

Sensor Issues

- Sensor Type – gold, silver, silver-chloride, tin, etc.
- Sensor location – at least one sensor placed on scalp
- Sensor attachment – requires electrolyte paste, gel, or solution
- Maintain an electrically secure connection

Sensor Types

- Disposable (gel-less and pre-gelled)
- Reusable disc sensors (gold or silver)
- Reusable sensor assemblies
- Headbands, hats, etc.
- Saline based electrodes – sodium chloride or potassium chloride

EEG Instrumentation

- Sensors pick up skin potential
- Amplifiers create difference signal from each pair of sensors
- Cannot measure "one" sensor, only pair
- 3 leads per channel – active, reference, grnd
- Each channel yields a signal consisting of microvolts varying in time

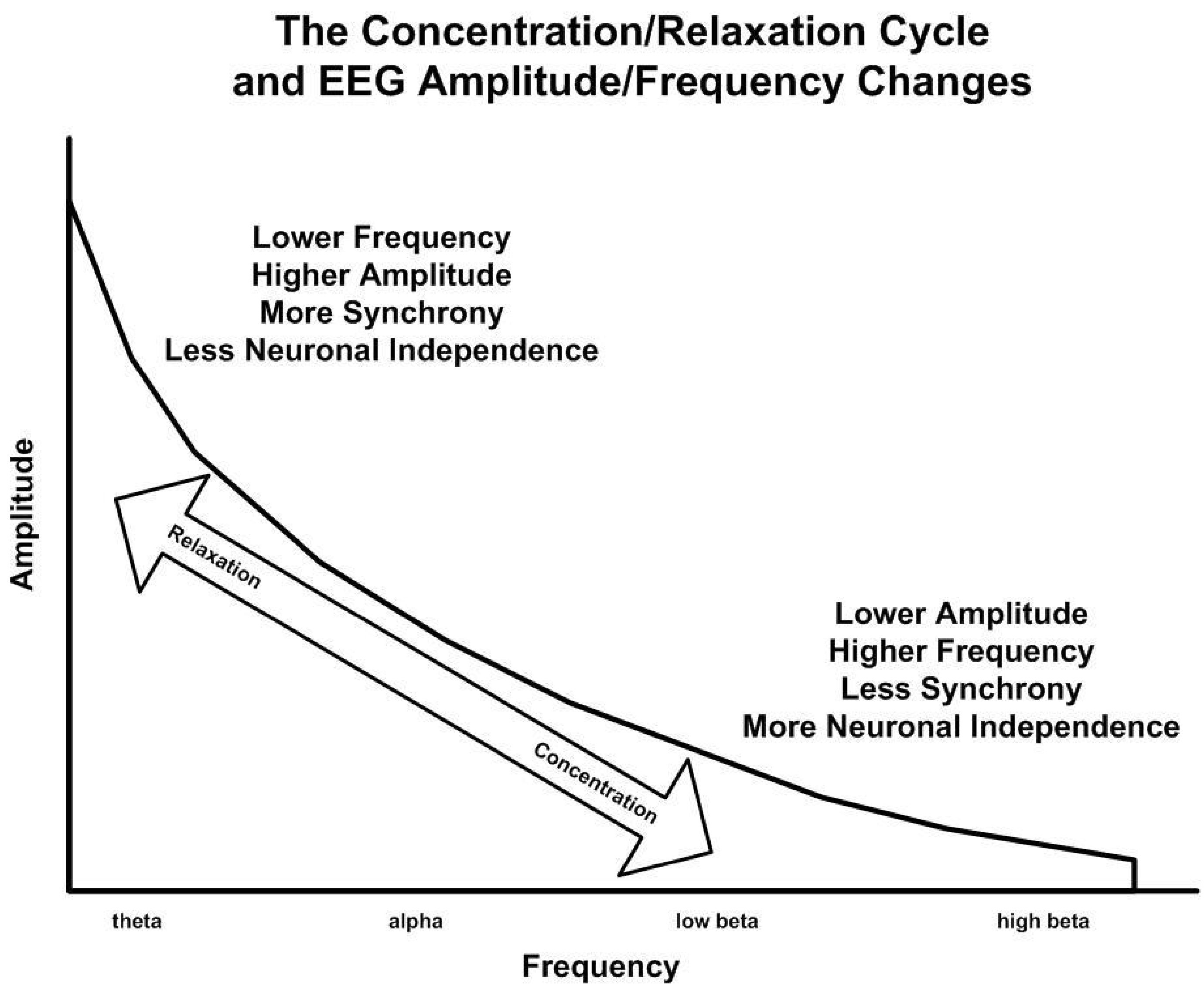
EEG Generation Mechanisms

- Primary mechanism of brain is inhibition
- Rhythms generated when inhibition is relaxed
- Allows thalamocortical reverberation
- Relaxation at cortical level, and at thalamic level
- Allows populations to oscillate in synchrony

Concentration/Relaxation Cycle

- Discovered by Dr. Barry Sterman in pilots
- “good” pilots preceded each task item with high-frequency, low-amplitude EEG
- Also followed task item with low-frequency, high-amplitude EEG (“PRS”)
- Poorer pilots did not exhibit control of the concentration/relaxation cycle
- Slower reaction time, more fatigue

Concentration/Relaxation Cycle



Neurofeedback Goals

- To teach brain flexibility, options
- To provide information for brain to learn
- Not necessarily to make “big” things “small” or vice versa
- To manage dysfunction at a systemic level
- To facilitate self-organization

Computerization

- Digitization – converts from analog to digital
- Sampling Rate – how fast signal is sampled
- Sampling Resolution – how fine-grained
- Processing Model – spectral analysis or filtering, thresholding, displays, sound feedback, etc.

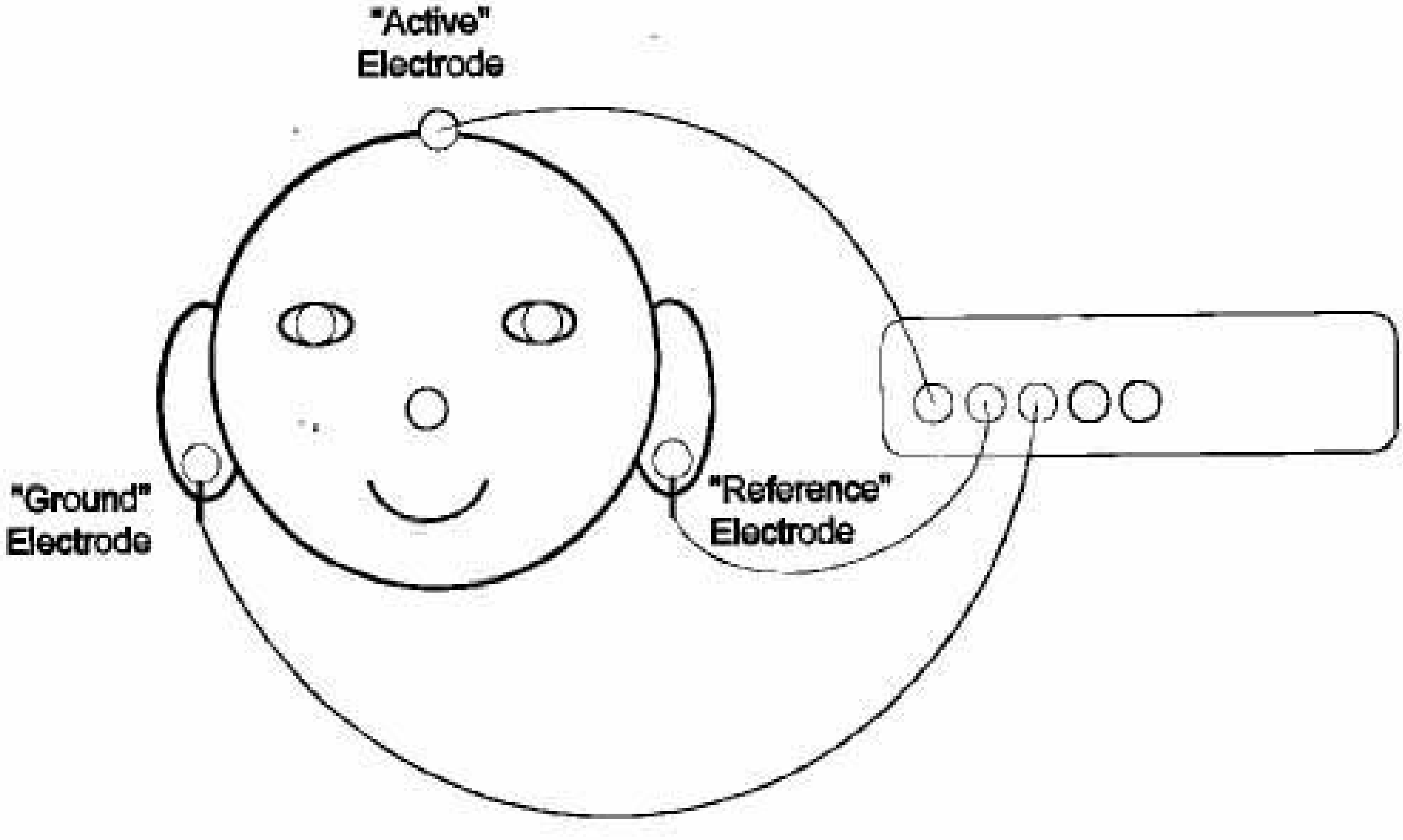
Signal Processing

- Digital filters or similar algorithms selectively measure frequency information
- Protocol processing via. thresholds, etc.
- Computer produces graphics, sounds

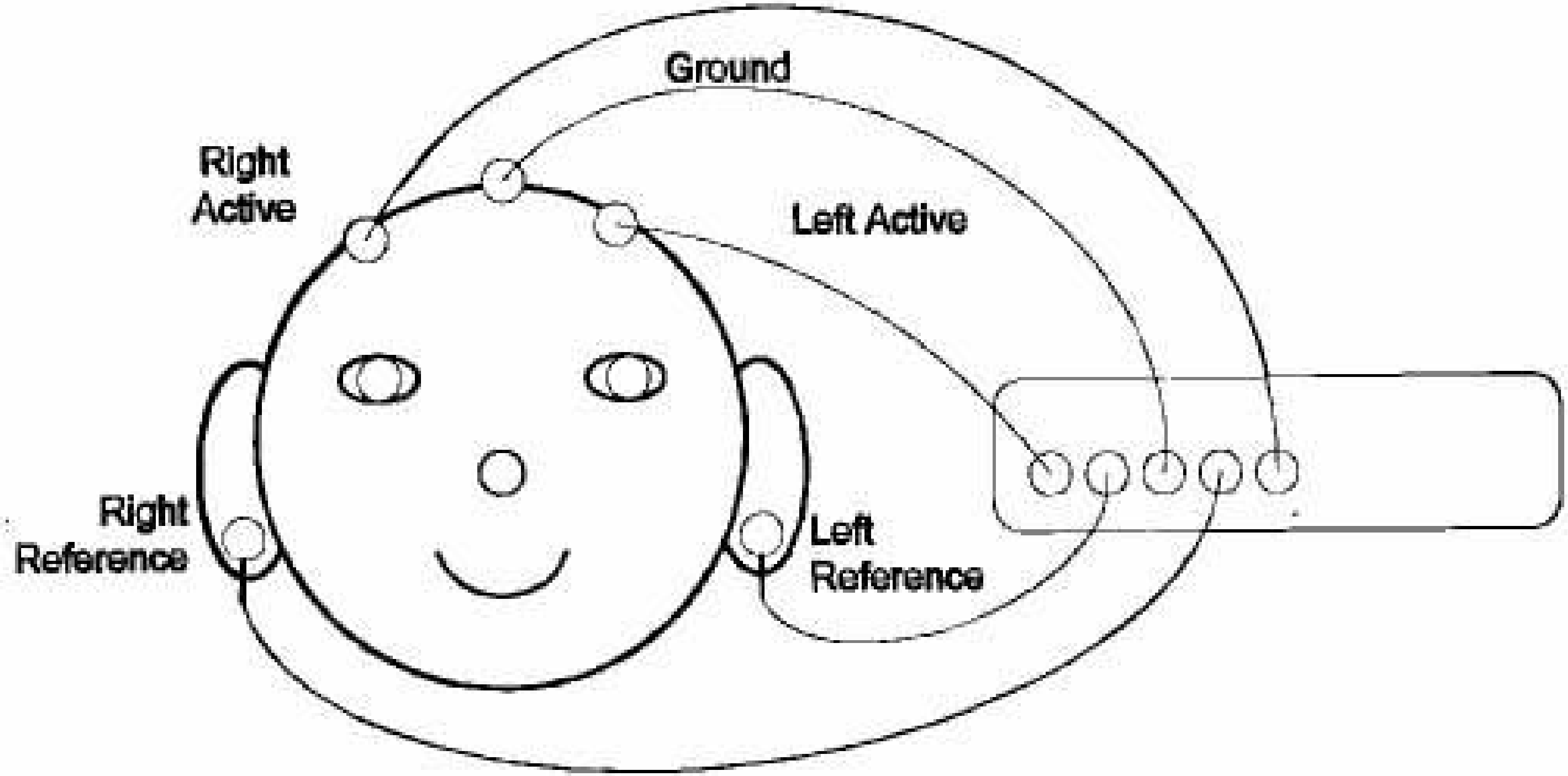
User Interfacing

- Displays – bargraphs, meters, animations, DVD’s
- Sounds – beeps, tones, music
- Manual Control – set thresholds manually
- Automatic Control – set thresholds automatically

One Channel Recording



Two Channel Recording



EEG Signal

- Microvolt levels – typically 5 – 50 uV
- Monopolar or Bipolar sensor placement
- 1 or 2 channels (or more)
- 0.5 - 40 Hz typical, more recently 0.0 – 60+
- "Composite" wave – combines all brain activity into a single wave from each site

Digital Filters

- Mathematical Processing in real-time
- Continuous data analysis
- Point-by-point results
- Any frequency bands possible
- Many types of filters possible
- Generally fast response, restricted to defined bandwidth

Digital Filtering

- Bandpass filter is like a colored glass
- Passes only the frequencies designated
- Separate components by bands
- Frequency response (bandwidth and center frequency)
- Time response (time-constant, and "resonance")

Filtering Dynamics

- Alpha bursts generally 100 – 500 msec long
  - May be 1000 msec in meditators
- SMR bursts generally 80 – 200 msec long
- Gamma bursts generally 20 – 50 msec long
- Training filters must be able to follow waxing and waning, i.e. bursts

Filtering Dynamics

- Wider filter follows waxing and waning better
- Need filter bandwidth >= 1 / burst length
- E.g. to see a 250 msec burst, filter must be 4 Hz wide
- To see a 100 msec burst, filter must be 10 Hz wide

Filter Order

- Describes slope of “reject” area outside of main passband
- Low order = “shallow” skirts
  - Faster, but less selective
- High order = “steep” skirts
  - Slower, but more selective
- Typical values 2, 3, … 6 order filters

Filter order recommendations

- Low order (2, 3)
  - High frequency training – SMR, beta, gamma
  - Beginners, children, peak performance
  - Response has more "pop", picks up short bursts
- High order (5, 6)
  - Low frequency training – theta, alpha
  - Advanced, adults, meditation
  - Response is more accurate, requires longer bursts

Quadrature Filter

- Readily adjustable center frequency
- Transient response independent of center frequency
- No envelope detection delay
- Perfectly symmetrical pass bands
- Guaranteed zero phase shift
- Adaptable to coherence, comodulation
- (Collura, IEEE 1990)

FFT Analysis

- Fast Fourier Transform
- Like a prism – breaks signal into bands
- EEG data in “epochs” – chunks of time
- Frequency in “bins” – e.g. 1Hz, 2Hz, etc.
- Sees all frequencies at once
- Sliding window in time
- Accurate, but delay due to epoch length
- Useful for % energy, spectral correlation
- Generally accepted for assessment purposes

Signal Properties

- Amplitude – how large
- Frequency – how fast
- EEG components “wax” and “wane”
- Amplitude is a time average
- Frequency may be “peak” or “average” frequency

Thresholding

- Sets amplitude criterion for rewards
- Compares signal amplitude with set value
- Can be constant, or can be varying
- Percent time over threshold is indicator of how often signal exceeds threshold

Thresholding

- Threshold is generally amplitude value
- Feedback is controlled via thresholds for each trained component
- Component may be “enhance” (“go”) or “inhibit” (“stop”)
- May use more than 1 component in combination in a protocol
- “Percent time over threshold” (%TOT)is average time the component is above threshold

Threshold Targets

- Enhance – being over threshold allows positive feedback
  - Reward rate = % TOT
- Inhibit – being over threshold inhibits feedback
  - success is being below threshold
  - Reward rate would be 100 - % TOT
- Total reward rate is product of individual success rates for each component

Threshold Targets

- Low inhibit – 20% TOT
  - 80% success rate = 100 - 20
- Midrange enhance – 60% TOT
  - 60% success rate
- High inhibit – 10% TOT
  - 90% success rate = 100 - 90
- Expected reward rate:
  - 0.8 x 0.6 x 0.9 = 0.43 = 43%
- SMR enhance is emphasized

Threshold Targets – Example 1

- Theta inhibit – 20% TOT
- SMR enhance – 60% TOT
- Hi Beta inhibit – 10% TOT
- Expected reward rate:
  - 0.8 x 0.6 x 0.9 = 0.43 = 43%
- SMR enhance is emphasized

Threshold Targets – Example 2

- Theta inhibit – 40% TOT
- SMR enhance – 80% TOT
- Hi Beta inhibit – 10% TOT
- Expected reward rate:
  - 0.6 x 0.8 x 0.9 = 0.43 = 43%
- Theta Inhibit is emphasized

Threshold Targets – Example 3

- Theta inhibit – 60% TOT
- SMR enhance – 100% TOT
- Hi Beta inhibit – 0% TOT
- Expected reward rate:
  - 0.4 x 1.0 x 1.0 = 0.40 = 40%
- Theta Inhibit is all there is – Theta “squash”

When to adjust thresholds?

- Never (Lubar)
  - Don't frustrate trainee
  - Allow to see improvement in scores
- Once for each session (Ayers)
  - Tell trainee new threshold
  - Goal of consistent number of points per session
- Every 2-5 minutes (Othmer, Soutar)
  - Optimal rate of reward
  - Show trainee improvement in EEG scores
- Continually (Brown & Brown)
  - Brain is a dynamical system
  - Provide information regarding emergent variability

Squash Protocol

- Based on downtraining amplitude
- Generally directed toward activation
- Lower amplitude -> higher frequency
- "Bench press" model – work then relax
- Easy to learn, especially theta squash

EEG Components

- Bands do not define components
- Bands describe components
- Components may share frequency band ranges

EEG Components (typical ranges)

- Delta 1 – 3 Hz
- Theta 4 – 7 Hz
- Alpha 8 – 12 Hz
- Lo Beta 12 – 15 Hz (SMR)
- Beta 15 – 20 Hz
- High Beta 20 – 35 Hz (may contain EMG)
- Gamma 40 Hz

Delta (typ. 1 – 3 Hz)

- Distribution: broad, diffused, bilateral, widespread
- Subjective states: deep, dreamless sleep, trance, unconscious
- Tasks & behaviors: lethargic, not attentive
- Physiological correlates: not moving, low-level arousal
- Effects: drowsiness, trance, deeply relaxed

Theta (typ. 4 – 7 Hz)

- Low-frequency rhythm associated with internalized thoughts
- Mediated by subthalamic mechanisms
- Associated with memory consolidation
- Generally non-sinusoidal, irregular
- Seen during hypnogogic reverie
- Seen as precursor, and sequel to sleep
- Edison's "creativity" state

Theta (typ. 4 – 7 Hz)

- Distribution: regional, many lobes, laterlized or diffuse
- Subjective states: intuitive, creative, recall, fantasy, imagery, dreamlike
- Tasks & behavior: creative, but may be distracted, unfocussed
- Physiological correlates: healing, integration of mind and body
- Effects: enhanced, drifting, trance like, suppressed, concentration, focus
- Typically 4 – 8 Hz

Three types of “theta”

- “True” theta
  - Subthalamic control
- Slow alpha
  - Slowed due to increased processing
  - Evident in adults, meditators
- Glial theta
  - DC potential, modulated at up to 4 Hz

Alpha (typ. 8 – 12 Hz)

- Resting rhythm of the visual system
- Increases when eyes are closed
- Largest occipital – O1, O2
- Characteristic waxing and waning
- Generally sinusoidal, hemispheric symmetrical
- Indicates relaxation
- Role in background memory scanning
- Round trip thalamus-cortex-thalamus ~ 100 ms
- Typically 8 – 12 Hz, but may be 4 – 20 Hz

Alpha (typ. 8 – 12 Hz)

- Distribution: regional, evolves entire lobes, strong occipital with closed eyes
- Subjective states: relaxed, not drowsy
- Tasks & behavior: meditation, no action
- Physiological correlates: relaxed, healing
- Effects: relaxation

Alpha vs. activation

- Paradox – when alpha appears, brain is less active
- Activation is accompanied by high frequency, lower amplitude EEG
- Can achieve activation by training amplitude down – "squash" protocol

Frontal Alpha Asymmetry

- Davidson, Rosenfeld, Baehr found:
- Right alpha should be 10 – 15% > left alpha
- Required for positive mood
- Can train left alpha down to treat depression
- Activates left hemisphere

Two Alphas

- Alpha actually shows 2 bands
- May wax and wane independently
- 9 – 12 Hz
  - Standard resting rhythm
  - Typical occipital alpha wave
- 7 – 9 Hz
  - Related to emotional processing
  - Important to frontal asymmetry
  - Longer round-trip may indicate more processing

Low Beta (typ. 12 – 15 Hz)

- Distribution: localized by side and lobe
- Subjective states: relaxed, focused, integrated
- Tasks & behavior: relaxed, attentive
- Physiological correlates: inhibited motion (when at sensorimotor cortex)
- Effects: relaxed focus, improved attentive ability

Sensorimotor Rhythm (SMR) (typ. 12 – 15 Hz)

- Resting rhythm of the motor system
- Largest when body is inactive
- Indicates intention not to move
- Measured over sensorimotor strip C3/Cz/C4
- Round-trip thalamus-cortex-thalamus ~ 80 ms
- Typically 12 – 15 Hz
- Also called “14 Hz” or “Tansey” rhythm

Beta (typ. 16 – 20 Hz)

- Distribution: localized, over various areas
- Subjective states: thinking, aware of self and surroundings
- Tasks & behavior: mental activity
- Physiological correlates: alert, active
- Effects: increase mental ability, focus, alertness

High Beta (typ. 20 – 30 Hz)

- Distribution: localized, very focused
- Subjective states: alertness, agitation
- Tasks & behavior: mental activities (math, planning, etc)
- Physiological correlates: activation of mind and body functions
- Effects: alertness, agitation

Gamma ("40 Hz")

- AKA "Sheer" rhythm
- Collura (1985) found 6-7 bursts/second in PSI states using FFT technique
- Davidson found sustained gamma in advanced meditators
- Short bursts require wide (35 – 45) filters to detect
- Others define:
  - 25-30 Hz (Thatcher)
  - 32-64 Hz (Thornton)

Gamma ("40 Hz")

- Distribution: very localized
- Subjective states: thinking, integrated thoughts
- Tasks & behavior: high-level information processing "binding"
- Physiological correlates: information-rich tasks, integration of new material
- Effects: improved mental clarity, efficiency

DC ("Direct Current")

- Standing potential, 0.0 – 1 Hz
- Reflects glial, other mechanisms
- Includes sensor offset and drift
- May include "injury" potential
- Difficult to record, may be unstable
- Requires Ag/AgCl sensors
- SCP is more useful clinically

SCP ("Slow Cortical Potentials")

- Typically 0.01 – 2 Hz
- Primarily glial origin
- Associated with general brain activation
- "Bareitschaft" potential evident preceding voluntary motor movement
- Large shifts seen preceding seizures
- Training useful in epilepsy, BCI

Connectivity measures

- Coherence – constant phase separation
- Synchrony ("Similarity") – same size, in phase
- Phase – lined up peaks and valleys
- Correlation – similar spectral signature
- Comodulation – wax and wane together

Coherence Training

- Coherence reflects similarity between 2 channels
- Measure of information sharing
- Coherence may be trained up or down
- "Goldilocks" effect – may be too high or too low at any given site
- Alpha coherence can be trained up bilaterally (occipital or parietal) without adverse reaction

Z Scores

- Based upon normative database
- Z score = estimate # of standard deviations away from mean
- + means component is high
- - means component is low
- Z scores computed for amplitude, relative amplitude, ratios, coherence, phase
- Commonly used for assessment
- Can be used in real time for training

Effective Feedback

- Fast – provides timely information to allow temporal binding
- Accurate – so brain has good information to work with, not ambiguous or superfluous
- Aesthetic – so brain will respond well to the content of the feedback without undue effort or confusion

Instructions to Trainee

- Allow the sounds to come
- Do not “try” to do anything
- Allow yourself to learn what it feels like when you get a point
- Relax and pay attention to the screen
- Let the sounds tell you when you are in the desired state

Standard Protocols

- Alert C3 – beta up; theta, hibeta down
- Deep Pz – (Penniston) alpha up, theta up
- Focus C4 – SMR up; theta, hibeta down
- Peak C3-C4 – alpha coherence up
- Peak2 C3-C4 – alert and focus combined
- Relax Oz – alpha up; theta, hibeta down
- Sharp Fz – broadband squash

Additional Activities

- **Reading**
- **Legos**
- **Drawing**
- **Tetris**
- **Coloring book**
- **Puzzles**
- **Homework**
- **Allow trainee to attain relaxed, focused state even while under a task**

Low Freq vs. High Freq Training

Characteristics	Low Freq Training	High Frequency Training
Components	Alpha: reinforce Theta: reinforce	Beta: reinforced Smr: reinforced Theta: inhibited
Goal	Deeper awareness	Balance, control, alertness
Level of effort	Effortless, letting go	Effort, relaxed
Speed of response	Brain responds slow, feedback can be slow	Brain responds quickly, rapid feedback
Use of feedback	Primarily an indicator	Want to “crank” thresholds & perform
Reward percent	Generally 80%	Generally 50-60%
Type of feedback	Mostly “yes” some “no”	Mostly “no” some “yes”

Low Freq vs. High Freq (cont)

Characteristic	**Low Freq Training**	**High Freq Training**
Trainee context	Immersion into relaxed state	Tuning, improving brain
Application	Exploration and recovery	Mental fitness
Brain areas	Parietal, Occipital	Motor area
Modality	Auditory, trancelike	Visual, game like
Sessions	30min to 3hours no breaks	20-30min, may have breaks
Relaxation	Total relaxation	Relaxation with muscle tone
Environment	Quiet, low lighting	Normal surrounding
Clinical Use	Deep seated issues, recovery	Attention, Depression, Other

Low Freq vs. High Freq (cont 2)

Characteristics	**Low Freq Training**	**High Freq Training**
Volition	Abandon volition	Has volitional element
Self-Improvement	Awareness, one-ness, growth	Peak-performance
Eyes	Eyes closed	Eyes open
Crossovers	Yes (from alpha state to theta state)	No
Increase	Look for 2x to 3x	Optional sustained increase
End state	Altered state of consciousness	Awake & alert state
Spatial	Widespread in space (brain)	Localized in space (brain)
Follow on goal	Experience altered state now, reap follow-on benefits	Ability to reproduce state during daily life
Age	Not done with children	All ages

System Overview

- Signals from brain are revealed to Trainee
- Brain processes new information & learns
- Allows conditioning and learning to occur
- System must be comprehensible, intuitive, relatively simple
- Element of volition, engagement – but not "trying"
- EEG outcomes vs. clinical outcomes