The Measurement, Interpretation, and Use of EEG Frequency Bands

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1. Introduction:

The EEG is an electrical waveform that is recorded from the brain by using electrodes appropriately placed on the head, then amplifying and displaying the electrical signal using a computer, or other suitable instrument. It consists of a wave that varies in time, much like a sound signal, or a vibration. As such, it contains frequency components that can be measured and analyzed, and these frequency components have interesting and valuable properties.

A great deal of history is involved in the definition, naming, and use of these frequency bands. They are named using Greek letters, a convention that was begun by Hans Berger, the discoverer of the EEG in humans. He observed all of the rhythms known today (except the 40 Hz "gamma" band), and described many of their basic properties. Since then, our definitions and understandings of the rhythms have been refined. However, there still remains some uncertainty, and controversy, in how to define and use these bands, for various purposes.

1.1 Approaches to understanding:

There are many ways to approach the understanding of brainwaves. Clinicians view them for diagnostic purposes, seek to identify patterns that associate with specific pathologies or conditions. Psychologists also study them in association with mental states, mental processing, and to test concepts of how the brain processes information. We also know from introspective reports, and structured experiments, which subjective states tend to be correlated with a predominance of the various brainwave components.

Brain rhythms can also be operantly trained, using biofeedback. By training an individual to learn how to produce (or reduce) specific frequencies, changes in the brain can be produced. From a training standpoint, we can learn what types of mental states or activities are affected by specific types of training. Similarly, we can learn which brain/mind states, qualities, or activities are associated with a preponderance of, or conversely a lack of, any particular rhythm or combination of rhythms.

Generally, we cannot tell from the EEG "what I am thinking" - but we may be able to say "You are thinking that this is interesting" or "You are thinking that this is not interesting"

We might be able to say "you cannot relax without drifting off" which is to read into another's introspective state, but not in terms of knowing what is the content of the thoughts.

It is important that we allow the brainwave signals to tell us what they have to say, and not try to force their meaning into familiar, predefined terms. For example, to expect the brainwave, in a primitive sense, to indicate, for example, "this is the rhythm for attention." or "this is when you are thinking 'up'", and so on, are ill-conceived. Rather, we need to study the patterns that emerge during various behavioral, as well as introspective, states, and then see what they are defining in terms of a multidimensional representation of some state-space.

Research that is focused on understanding specific properties, such as attention, alertness, mental acuity, etc., has uncovered combinations of rhythms, and other EEG properties, that are relevant to these studies. Generally, "derived" properties are found useful, that involve computer-processing of the EEG, to produce measurements that are useful for research, monitoring, etc.

1.2 How brain rhythms are generated:

Populations of cells generate rhythms when they depolarize in synchrony. This activity occurs primarily in the upper 4 layers (about 1/4 inch thick) of the outer layers of the cerebral cortex. The presence of an EEG rhythm indicates that there is some brain activity occurring in terms of millions of cells acting together, in a synchronized fashion. The exact causes of this, and what it means for the brain and information processing, is an entire dissertation in itself.

Overall, the observed brainwave frequencies must be thought of as "epiphenomena," which are the byproduct of normal brain function, but not a brain signal in themselves. The brain does not communicate, or do its business, using the EEG. Rather, it is a secondary measure, such as the vibration measured from an engine, or the temperature of an electronic circuit. Therefore, the brain does not, for example, produce alpha waves for any purpose. It produces them as a result of certian ltypes of brain activity, and we can learn to recognize them, and take advantage of them, by learning what they represent, and what happens when we work with them.

1.3 Distribution in Time and Space:

The brain consists of over 100 billion cells, organized into many different regions, all doing different things, all acting simultaneously. The brain is not a computer. It is an assemblage of millions and billions of computers. Therefore, at any time and any particular location, the brain may produce a combination of frequencies. Variations in time, and in space (observed as different places on the scalp) are important to understand.

EEG signals are seen to wax and wane, which means to grow larger and smaller, in time, generally showing moment-to-moment variation at all times. Alpha is almost always seen in "spindles" and "bursts," almost never seen in a continuous wave. It is the production of more, or larger, bursts of rhythmic activity, that is associated with their being a higher "amount" of that component. Beta, for example, may occur in very small bursts, of 1/10 second or less, so that it comes and goes very rapidly. Alpha, on the other hand, generally waxes and wanes with bursts of from about 1/5 second, up to 1 or 2 seconds in length.

Spatial distribution can be seen in all components. Some of these are described below. Since the brain consists of broadly identifiable areas (frontal (motor and sensory cortex), parietal, occipital (visual), temporal (hearing, language), rhythms are seen to be associated with the particular involved area. Electrode placement is therefore important when measuring or training for particular rhythms. Training at a location will affect the EEG activity primarily at that location.

The EEG is thus like a symphony, which is a complex mixture of sounds, changing in time and in space. The brain is a massively parallel processor that contains many thousands of cell systems. There may be a preponderance of one or more rhythms at any time, and this combination of frequencies, in time and in space, can help us to understand the condition, and the activities, of the brain. There has been work that suggests the existence of a specific "alpha state," for example. Even though the brain may be producing a preponderance of alpha waves at any instant, this does not necessarily suggest an "alpha state," per se. Brain states may exist, and they may be correlated with the presence or absence of various frequencies, in time and space, rather than just one frequency.

1.4 Training of EEG rhythms

Biofeedback techniques can be used to train EEG rhythms. Training systems can use visual feedback, auditory feedback (sounds), or use a personal trainer to provide verbal feedback, thus making the trainee aware of which brain rhythms are present. Displays can be of many types, and computer displays are capable of producing a wide variety of useful displays. These can include "thermometers", video games, and other graphic displays. Systems can be set up to train to reinforce, or to reduce, any rhythm or combination of rhythms, or for more complex situations such as training different locations to be synchronized, or desynchronized, or to train different locations to produce (or inhibit) different frequencies.

Early EEG training emphasized the production of a particular frequency, for example, alpha-wave training. More recently, the emphasis has been on training flexibility, or appropriateness, of brain rhythms. That is, the brain needs to produce the desired rhythms at the proper times, and in the proper locations. The development of these complex protocols is an important area of current research, and clinical development.

We can also train more complex, derived properties, such as brainwave synchrony, coherence, or relationships between brain rhythms recorded from different sites. This has been found particularly useful in training concentration and relaxation, for peak-performance training, and for athletics, golfers, etc. Certain EEG properties have been found conducive to being "in the zone," which is a highly efficient and responsive state, useful for improving performance in many applications.

It is important to realize that, although rhythms can be trained, to produce desired results, the production (or reduction) of the specific rhythm is not an end in itself, and the change in the EEG may not signify that the desired change has occurred. Rather, the desired brain/mind changes are a by-product of the training, independent of changes in the EEG itself. The brain is a self-regulating system, and may behave much like a thermostat, that tries to keep the system stable. To use an analogy, if a window is left open in a house in the winter, the house may not be cold, but the furnace will be working hard, and the heating bills will be high. If the window is closed, representing a return to normal operation, the temperature may not rise significantly, but the furnace will work less. Thus, the brain may achieve a desired state, even if the measured variable, the brain rhythms, do not change significantly, in and of themselves. Nonetheless, changes in the brain have occurred, and their benefits may be forthcoming, even in the absence of large changes in the EEG signal.

2. Summary of EEG Frequency Bands:

The basic EEG rhythms are summarized briefly as follows, with regard to their typical distribution on the scalp, subject states, tasks, physiological correlates, and the effects of training. This summary should be taken as a general roadmap, not as fixed and hard rules.

2.1 Delta (0.1-3 Hz):

Distribution: generally broad or diffused, may be bilateral, widespread
Subjective feeling states: deep, dreamless sleep, non-REM sleep, trance, unconscious
Associated tasks & behaviors: lethargic, not moving, not attentive
Physiological correlates: not moving, low-level of arousal
Effects of Training: can induce drowsiness, trance, deeply relaxed states

2.2 Theta (3-8 Hz):

Distribution: usually regional, may involve many lobes, can be lateralized or diffuse;
Subjective feeling states: intuitive, creative, recall, fantasy, imagery, creative, dreamlike, switching thoughts, drowsy; "oneness", "knowing"
Associated tasks & behaviors: creative, intuitive; but may also be distracted, unfocused
Physiological correlates: healing, integration of mind/body
Effects of Training: if enhanced, can induce drifting, trancelike state
if suppressed, can improve concentration, ability to focus attention

2.3 Alpha (8-12 Hz):

Distribution: regional, usually involves entire lobe; strong occipital w/eyes closed
Subjective feeling states: relaxed, not agitated, but not drowsy; tranquil, conscious
Associated tasks & behaviors: meditation, no action
Physiological correlates: relaxed, healing
Effects of Training: can produce relaxation

Subband low alpha: 8-10: inner-awareness of self, mind/body integration, balance
Subband high alpha: 10-12: centering, healing, mind/body connection

2.4 Beta (above 12 Hz)

The beta band has a relatively large range, and has been defined as anything above the alpha band.

2.4.1 Low Beta (12-15 Hz), also called "SMR":

Distribution: localized by side and by lobe (frontal, occipital, etc)
Subjective feeling states:relaxed yet focused, integrated
Associated tasks & behaviors: low SMR can reflect "ADD", lack of focused attention
Physiological correlates: is inhibited by motion; restraining body may increase SMR
Effects of Training: increasing SMR can produce relaxed focus, improved attentive abilities, may remediate ADD.

2.4.2 Midrange Beta (15-18 Hz)

Distribution: localized, over various areas. May be focused on one electrode.
Subjective feeling states: thinking, aware of self & surroundings
Associated tasks & behaviors: mental activity
Physiological correlates: alert, active, but not agitated
Effects of Training: can increase mental ability, focus, alertness, IQ

2.4.3 High Beta (above 18 Hz):

Distribution: localized, may be very focused.
Subjective feeling states: alertness, agitation
Associated tasks & behaviors: mental activity, e.g. math, planning, etc.
Physiological correlates: general activation of mind & body functions.
Effects of Training: can induce alertness, but may also produce agitation, etc.

2.4.4 Gamma (40 Hz):

Distribution: very localized
Subjective feeling states: thinking; integrated thoughts
Associated tasks & behaviors: high-level information processing, "binding"
Physiological correlates: associated with information-rich task processing
Effects of Training: not known

3. Measuring frequencies

Frequencies may be measured in several ways. One is to use a Fast Fourier Transform (FFT) to estimate the amount of energy for all frequencies, in a defined interval of time, usually about 1 second. This is accurate, but lacks fast response, if training is a primary goal. Filtering is also used, which provides a faster response, but is limited to specific bands. Digital filters are implemented using computer software, and are a preferred method for training, due to their superior response to short transients, and to other changes in the signals over short periods of time.

Simple Guide to common EEG Protocols

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Note that these are all general guides, and may be changed for your preference

SMR Training (1 channel):

- Use: General brain fitness, organization, alertness
- Active (blue) C4 (right side, halfway between Cz and top of right ear)
- Reference (yellow): Right ear
- Ground (black): Left ear
- Eyes: open
- Protocol: "lobethet" = "Go" on lobeta, "Stop" on theta
- Optional: "Stop" on hibeta (to inhibit muscle artifact)
- Display: raw waveform, filtered waveform, thermometers, Brainmirror
- Frequencies: Select theta, lobeta for viewing
- Game: Can view "Xwing" or "Pacman" game if desired
- Sounds: Use regular reward sounds from "Play" mode, select preferred sound from "sound" menu pulldown (click, cymbal, etc)

Beta Training (1 channel):

- Use: Brain "brightening", reduce lethargy or depression
- Active (blue) C3 (left side, halfway between Cz and top of left ear)
- Reference (yellow): Left ear
- Ground (black): Right ear
- Eyes: open
- Procotol: "betathet" = "Go" on beta, "Stop" on theta
- Optional: "Stop" on hibeta (to inhibit muscle artifact)
- Display: raw waveform, filtered waveform, thermometers, Brainmirror
- Frequencies: Select theta, beta for viewing
- Game: Can view "Xwing" or "Pacman" game if desired
- Sounds: Use regular reward sounds from "Play" mode, select preferred sound from "sound" menu pulldown (click, cymbal, etc)

Basic Relaxation Training (1 channel):

- Use: Relax but stay alert.
- Active (blue) C3 or C4
- Reference (yellow) Left ear if C3 active, right ear if C4 active
- Ground (black): Other ear
- Eyes: open or closed
- Protocol: "alphathet" = "Go" on alpha, "Stop" on theta
- Optional: "Stop" on hibeta (to inhibit muscle artifact)
- Display: raw waveform, filtered waveform, thermometers, Brainmirror
- Frequencies: Select alpha for viewing. Make sure theta is not viewed.
- Game: No game is recommended.
- Sounds: After entering "Play" mode, use "Sounds" menu to select "component sounds". Then will hear nature sounds for alpha. Do not want to hear theta sound, so make sure theta is not viewed.

Deep Relaxation Training ("Penniston Protocol") (1-channel):

- Use: Relax and enter deep relaxed state.
- Active (blue) C3 or C4 or Cz or O1 or O2
- Reference (yellow) Left ear if C3 or O1 active, right ear if C4 or O2 active, either if Cz active.
- Ground (black): Other ear
- Eyes: closed
- Protocol: "Go" on alpha, "Go" on theta
- Optional: "Stop" on hibeta (to inhibit muscle artifact)
- Display: raw waveform, filtered waveform, thermometers, Brainmirror
- Frequencies: Select alpha and theta for viewing.
- Game: No game is recommended.
- Sounds: After entering "Play" mode, use "Sounds" menu to select **"component sounds"**. Then will hear nature sounds for alpha and for theta. As you enter a deeper relaxed state, the theta sounds will be heard more.

Notes: Cz is the very top of the head, between the ears. O1 is the left occipital lobe, O2 is the right occipital lobe.

Applications of Small Brainwave Machines

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Introduction

The low-cost, portable EEG machine has a short history. 1 and 2-channel units for under $1000 have only been available during the 1990's. As such, applications are in an embryonic stage. Nonetheless, a wide range of applications have been identified, and are being actively pursued. These include:

1. EEG Biofeedback
   - Personal/self-improvement/meditation
   - Therapist-guided relaxation, etc.
   - Peak-performance training, "Brain calisthenics"
   - Adjunct to EMG, GRS, etc.
   - Treatment of ADD & other clinical disorders
2. Computer Control & Communication
   - "Thought-controlled" cursor, switch
   - Brainwave-controlled games
3. Entertainment, Virtual Reality
   - Control of music, graphics
   - Control of VR Displays
   - Interface to Light/Sound machines
4. Education, Research
   - Labs, experiments, demonstrations
   - Monitoring classroom/audience attention
5. Military, Commercial
   - Screening & evaluating pilots, operators
   - EEG-based Cockpit controls, pilot monitoring
   - Assessing consumer reactions

Each of these application areas has its own requirements, history, and prospects for low-cost EEG.

EEG Biofeedback

EEG was first explored as a biofeedback modality by Kamiya, Brown, and others, beginning in the 1960's. Initial work led to a generalized relaxation model, based primarily on the alpha rhythm. Training was often done solely for the strengthening of the alpha rhythm, without regard for other variables, or other brain rhythms. It was found that developing the alpha rhythm, in and of itself, had limited value. Continued work has developed methods that use other rhythms, or combinations of rhythms, in both encouragement and discouragement protocols, to teach users to control the relative amounts of rhythms, providing much more precise control of the brain.

Computer Control & Communication

The use of the EEG to control or communicate with a computer is an application that has undergone slow but steady development since the 1960's. Early work by Pinneo and others attempted to record "latent motor potentials" caused by a person thinking a work, such as "up" or "down." More recently, investigators have been looking for signals that appear controllable, and adapting the system to them. One of these is the "sensorimotor rhythm" (SMR), that has been found to be under a certain amount of conscious control. Generally, the user uses "affective" thoughts, such as "feeling light" or "stopping thinking" to cause the desired rhythm.

Entertainment, Virtual Reality

Entertainment application include EEG-controlled composition and performance, including "audience-participation" situations.

Virtual Reality displays can use EEG to modulate, alter, or otherwise control any aspect of the virtual world. For example, a system could be made sensitive to the individual's overall cognitive and emotional state, to produce an appropriate world. This could include changing the colors or sizes of objects, controlling sunrise and sunset, or causing the appearance or removal of features, or even of the entire location.

Education, Research

EEG is not well known below the level of the graduate student. Very few colleges, and no known high schools, offer any opportunity for students to record, study, and understand the EEG. This is unfortunate, because it is becoming increasingly clear that a basic understanding of the EEG and its properties, especially with personal experience of recording (ideally one's own) EEG, can provides valuable insight into the brain, as well as the mind. For example, individual differences can be seen in EEG patterns between people, and EEG changes in various tasks or circumstances can also be revealing. It would be desirable for a greater number of students, at and below the undergraduate level, to have direct experience with, and understanding of, the EEG.

There is a certain amount of popular use of phrases like "left brain," "right brain," "being in synch," "alpha waves," and other related concepts. We like to understand how the brain operates, but often use concepts that we must for the most part, take for granted, because there is no practical way to check any of these ideas out. With the availability of low-cost, scientifically sound brainwave monitors, it becomes possible to effectively record and see anyone's brain rhythms, their left and right-brain activity, balance, synchrony, and other variables.

Military, Commercial

The military has a long history of studying the EEG; some of the earliest telemetric monitoring and analysis was developed by NASA during the 1960's, in connection with the space program. This was designed primarily to monitor the pilots' state of health and consciousness. In addition, the Air Force has had a long-standing program to develop EEG-based pilot controls for the cockpit. These include evoked-potential based system, which attempt to rapidly detect and act upon changes in the pilot's gaze, or level of attention, to a display item.

Another ongoing area is alertness monitoring for commercial and military transportation systems. Initial work used the ongoing EEG, and more recent work uses event-related potential, and neural networks to interpret the waveforms.

Purely commercial applications include studying subjects who are viewing advertising material or evaluating products, primarily to assess their level of interest and/or arousal.

Quadrature Filtering for Real-Time EEG Biofeedback

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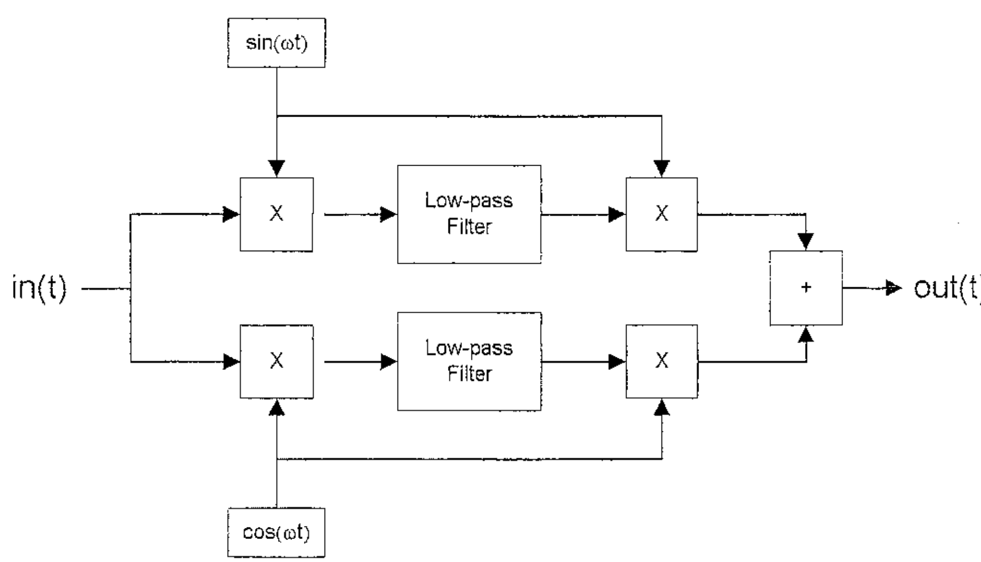
Filter Description

The Quadrature filter, also known as the "Weaver" filter, or the "Modulating" filter, is a very flexible, efficient, and accurate method for creating bandpass filters for signal processing. It is also related to methods known as "synchronous demodulation," or "heterodyning." Its application to EEG was described by Collura (1978, 1990, 1996), and has been proven effective in analog as well as digital implementations.

The structure of the quadrature filter is as follows:



The filter operates by using local reference signals that are in quadrature phase (sin and cosine), and using them to compute time-estimates of the Fourier coefficients of the signal, in real time. These time-estimates appear at the outputs of the low-pass filters, and contain all the information about the signal, in two slowly varying values. When recombined with the reference signals, the original input can be reconstructed in a filtered form. Alternatively, the low-pass filter outputs can be combined as a "square root of the sum of the squares," to resolve the amplitude component. In addition, phase information is available as the inverse tangent of the ratio of the two values.

The mathematics of the quadrature filter show that the overall filter characteristic is identical to that of the individual low-pass filters, only "slid" on the frequency axis, to be centered at the local reference frequency. As a result, the filter characteristic is always predictable and stable, regardless of where the center frequency is placed, or how wide the passbands are.

Advantages of the quadrature filter

Quadrature filters have the following advantages over conventional digital filters:

Readily adjustable center frequency: The center frequency of the filter is set by the local reference source, which is the frequency of a local sine wave. Therefore, as the filter center frequency is changed, there is no need to recompute the filter coefficients. The center-frequency is thus adjustable with arbitrary precision, and can be set to track any desired frequency.

Transient response independent of center frequency: The transient response is set by the low-pass filters alone. Therefore, a 3 Hz wide filter set at 4 Hz will have a transient response (ability to track rapid changes in the EEG) identical to that of a 3 Hz wide filter set at 15 Hz. As a result, all EEG components can be tracked with the same filter response characteristics, providing uniformity and consistency for EEG training.

No envelope detection delay: The quadrature filter computes, internally, the amplitudes of the inphase and out-of-phase components, as the outputs of the low-pass filters. These values can be combined directly, to produce the amplitude of the signal at any instant. Therefore, it is not necessary to perform an envelope detection operation on the filtered waveform. Envelope detection causes an additional delay, since it always lags the signal.

Perfectly symmetrical passbands, centered exactly at the center-frequency.

Guaranteed zero phase shift at the center of the passband.

Application in the BrainMaster

The BrainMaster uses quadrature filters for all internal filter operations. The low-pass filter is a 6th-order Butterworth filter, realized as an IIR filter. This is a very stable filter, with minimal overshoot, and excellent transient response. This filter provides a rolloff of 36 dB per octave, based on the 1/2 width of the filter.

For example, if a filter is set to pass 12-15 Hz, the low-pass filters will be 1.5 Hz wide, with a center frequency of 13.5 Hz. Therefore, the -3dB points will be at 12 and 15 Hz. One octave beyond that will be 3 Hz away from the center. Therefore, at 10.5Hz and 16.5 Hz, the response will be -36dB down, a factor of nearly 100.

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