Electroencephalography & Neurofeedback

A Brief Introduction to the Science of Brainwaves

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Introduction

This article is a brief introduction to electroencephalography or EEG, and its relevance to therapy with neurofeedback. Neurofeedback is an attempt to train or condition the EEG through feedback, in the hope of alleviating symptoms. EEG is a complex field and this introduction will necessarily leave out much of the detail. Nonetheless I hope it will provide a useful background for people thinking of beginning neurofeedback.

What Is Electroencephalography?

EEG is simply an oscillating electrical voltage recorded from the scalp. Examples are shown in figures 1 and 2, below. The "size" of the EEG, or more technically the *amplitude* (vertical axes in the figures), is just a few tens of microvolts (millionths of volts) - a subtle phenomenon requiring careful measurement.

Often we see rhythmic patterns within the EEG - figure 1 shows one. We can see from the scale of the graph that the EEG cycles around 10 times a second. Another way of putting this is that the EEG has a *frequency* of 10 Hertz. Rhythms of this frequency are known as alpha - named by Hans Berger who first discovered the EEG in 1929. Alpha is a common rhythm - it was the first that Berger discerned.

At times rhythms of other frequencies appear in the EEG. What rhythm we see depends on the brain's state of activation. As you might guess, the various rhythms correspond (loosely) with various mental states. Here we list some broad categories of EEG rhythm (which are also known as brainwaves).[1]

Delta (1 - 4 Hz)

Delta rhythm is seen in adults in deep sleep. It appears to be produced when the cortex is "offline" - it's also seen in some cases of brain damage. It's the predominant rhythm seen in very young infants.

Theta (4 - 8 Hz)

Theta activity corresponds to drowsy or day-dreamy, internally-oriented mental states. It can also be quite a creative state in which dream-like images and intuitive thinking come to the fore.

Alpha (8 - 12 Hz)

Alpha is associated with open, calm and relaxed awareness. It is seen mostly when the brain is not actively engaged in processing - it is sometimes known as the "idling" rhythm. The cortex is

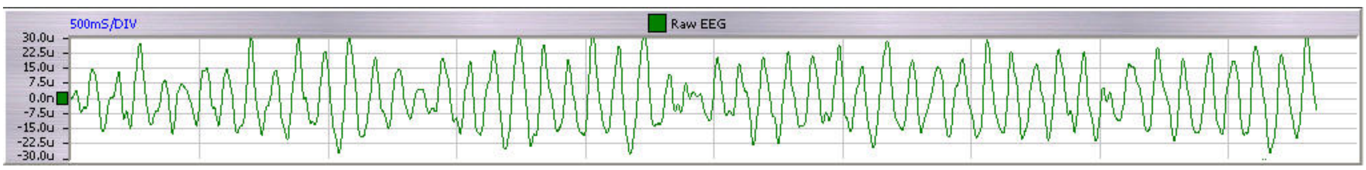

Figure 1: a relatively rhythmic EEG. Though the amplitude (vertical axis) varies, the duration (horizontal axis) of each cycle is stable, at around 1 cycle per 0.1 seconds - a frequency of around 10 Hz.

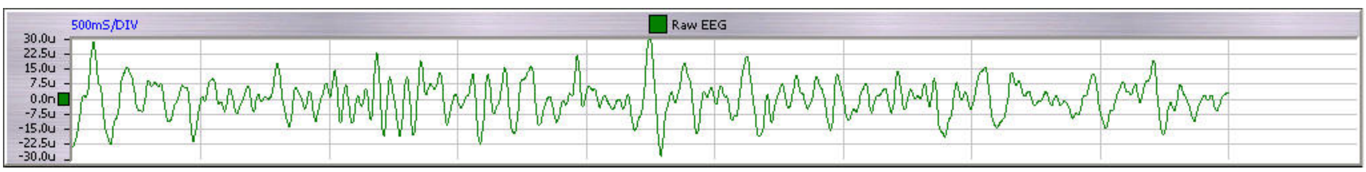

Figure 2: An EEG recording with no discernable rhythm.

online but not busy. In athletes it is associated with fast reflexes, being “in the zone” - at least for alpha in the upper part of the frequency band.

Beta (13 - 36 Hz)

Beta covers a broad frequency band. Subjects producing beta are usually alert and engaged with their surroundings. Activity in the range 16-20 Hz is associated with normal thinking and problem solving, but faster frequencies are associated with anxiety and hyper-vigilance.

Gamma (38 - 42 Hz)

The gamma band seems to be connected with conscious attention and is discussed later in connection with the “binding mechanism”.

Non-rhythmic EEG

EEG rhythms are intermittent - sometimes only lasting a fraction of a second. (By ‘rhythm’ I mean EEG with a clear cycling pattern and relatively stable frequency.) We have seen that we can characterise EEG rhythms in terms of frequency and amplitude, but how do we make sense of the EEG when there is no particular rhythm present, such as in figure 2?

In such cases, scientists use mathematical tools to analyse the EEG. This opens up a huge field, mostly beyond the scope of this article. Here I’ll mention just a couple of these tools: spectral analysis I shall describe more fully in the following section, and coherence analysis, which is a way of measuring how closely related two regions of the brain are, in terms of EEG.

Spectral Analysis

Spectral analysis is based on a mathematical theorem which says that a complex oscillation such as that shown in figure 2 is made up of lots of “pure waves”, or sine waves, of different frequencies, (see figure 3) added together in differing proportions.

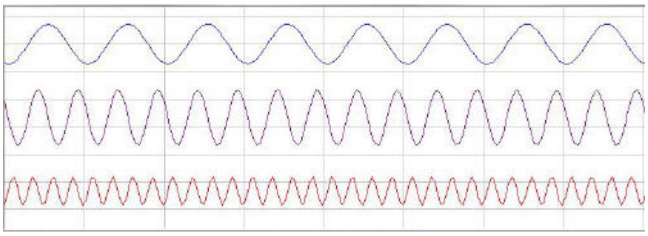

Figure 3: sine waves ranging in frequency

In spectral analysis we break down the complex oscillation into components. The result is a graph such as figure 4, which shows the relative proportions of the different frequency components that make up the EEG.

Rhythms such as alpha or delta now correspond to frequency bands - alpha, for example, is 8 - 12 Hz. Figure 5 shows the spectral analysis of the EEG shown in figure 1 - note the high peak around 10 Hz which corresponds to the alpha rhythm.

Note that a spectral analysis is an approximation of the actual EEG, but it does give useful information.

EEG Variation Across the Scalp

By now you’ll be beginning to appreciate that the EEG is a pretty complex phenomenon. All the more so when you realise that it’s not the same

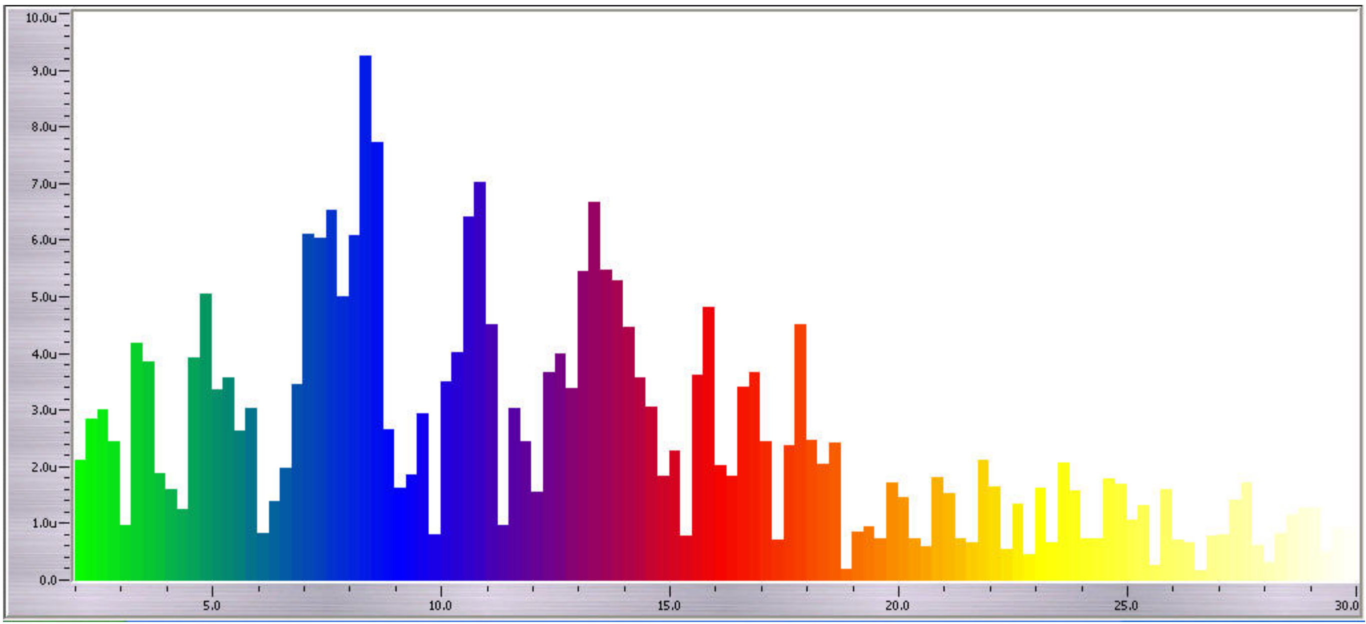

Figure 4: Spectral analysis of EEG shown in figure 2 - mixed frequencies.

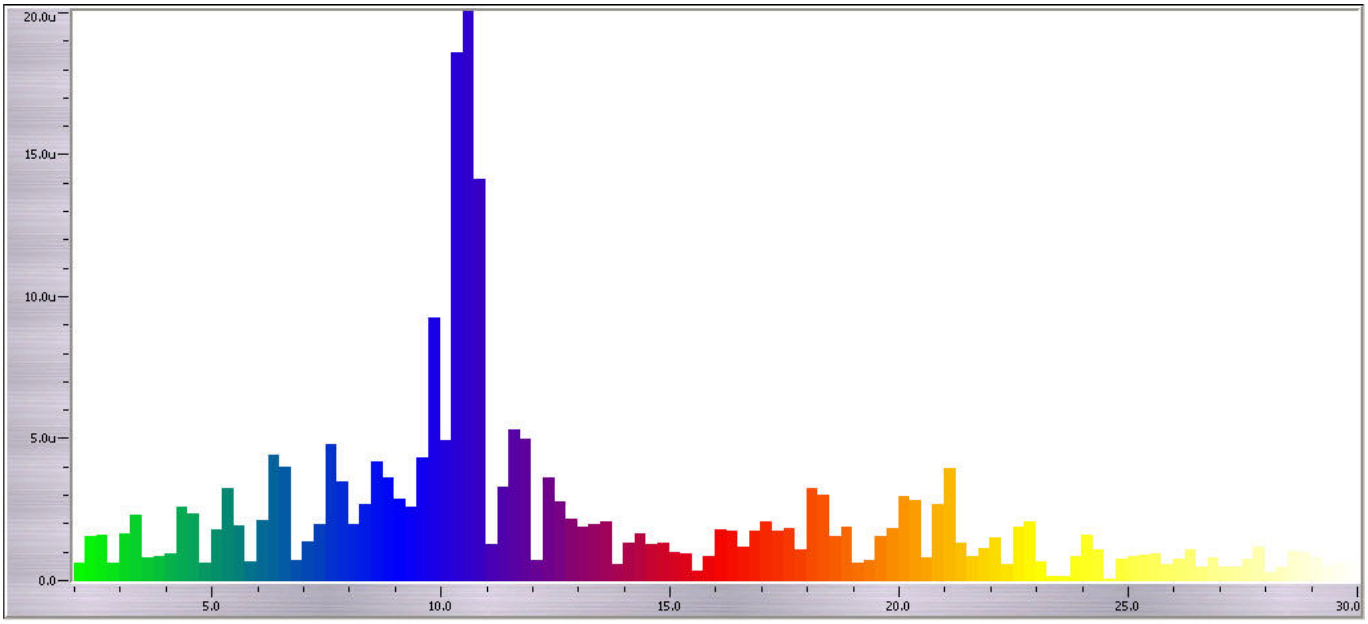

Figure 5: Spectral analysis of EEG in figure 1. Note the high peak around 10 Hz - this corresponds to the alpha rhythm.

over the whole head, but varies depending on where you place the sensors.

A full recording of EEG typically involves attaching many sensors or electrodes across the whole scalp. A common number is 19 but cutting-edge research uses as many as 256. The result is sometimes referred to as a Quantitative EEG or QEEG.

Scientists have built up databases of EEG from large numbers of people, and from this data have been able to describe general patterns of variation across the scalp.[2]

More About Alpha

The alpha rhythm is usually seen most prominently at the back of the head. Under the very back of your skull are the brain's occipital lobes (one on each side), and these are given over to processing visual information. Alpha is seen most prominently when the eyes are closed - opening the eyes produces are large reduction in alpha activity. Remember alpha is a kind of "idling rhythm". When the eyes are closed, the visual areas of the brain are not actively processing, so we see alpha over the occipital lobes.

Asymmetries

More generally speaking (whether the eyes are open or closed), we expect to see alpha levels drop off as we move from the back to the front of the head. Conversely, we expect to see beta levels increase from back to front. To some extent, alpha and beta are in inverse relationship - the more of one is present, the less of the other.

A similar relationship exists between the left and right hemispheres of the brain. We expect to see slightly more beta on the left side, and slightly more alpha on the right.

Origin and Function of the EEG

The electrical voltages that produce the EEG originate in neurons of the cortex - the brain's outer (and evolutionarily speaking most recent) layer of the brain. No other parts of the brain produce EEG.

A particular type of cell in the cortex - the pyramidal cells - develop a region of electrical polarisation in their dendrites ("input branches"). Each cell on its own can only produce a tiny voltage, but when millions of such cells, which are aligned parallel to each other and perpendicular to the surface of the brain, act in concert, the voltages combine to create an effect measurable on the scalp. EEG is only indirectly related to action potentials - the electrical pulses by means if which neurons communicate.

How do the cells act in concert? It seems that to some extent they fall under the influence of pacemakers, which act like the conductor of an orchestra - they set the timing so that everyone can play together. The brain's major pacemaker is the thalamus, a nucleus right in the centre of the brain (in fact there are two of them). The thalamus can generate rhythms of up to around 12

Hz. Faster rhythms (i.e. beta) seem to be generated by the cortex itself.[3]

What function does the EEG serve? As yet there is no clear-cut answer to this question. Some scientists have even questioned whether the EEG has a function at all - it may be just a side-effect.

One idea is that some rhythms provide a gating mechanism for incoming sensory information. This fits with the knowledge that the thalamus appears to be a sensory relay station - most incoming sensory data passes through the thalamus on its way to the cortex. It could be that by altering the EEG the thalamus provides a way to switch off the input, so that the cortex can get on with some other task (e.g. sleeping). Certainly the thalamus is involved in attentional control.

Gamma - the Binding Rhythm?

Another speculation is that one particular EEG rhythm - gamma - provides the brain with its (so-called) binding mechanism.

We know that different neural networks in different parts of the brain process different information - e.g. in the visual system, colour information or movement information. Yet our conscious experience is a unified whole - we experience colour and motion together in one object, say a fire engine. The brain must have some mechanism for integrating the disparate computations - this is the hypothesised binding mechanism. Certainly it is observed that large parts of the cortex generate synchronous gamma activity (40 Hz) in moments of conscious attention.[4]

EEG and Disorders

Is it possible to see differences in the EEGs of people suffering from particular neurological and psychological disorders, compared to “normal” people? Broadly speaking the answer is yes - at least for some disorders. We must qualify this by emphasising that most disorders - certainly psychological disorders - are diagnosed according to symptoms, not the EEG. In this section we’re speaking about statistical correlations - they don’t apply to every single case. Less is known about causal relations between EEG and disorders.

We’ll look at just a few disorders.

Epilepsy

Epileptic seizures have been described as electrical storms in the brain. They are characterised by very high amplitude waves in

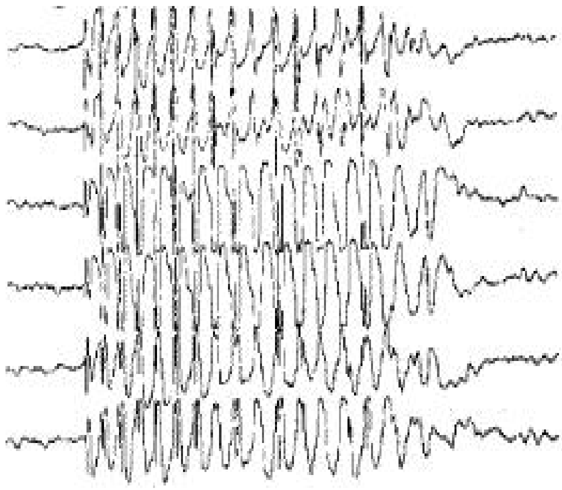

Figure 6: EEG during a brief epileptic seizure.

the EEG. Neurologists use EEG to help diagnose epilepsy. There are many types of epilepsy, and symptoms range from mild “absences” to violent jerking, in relation to the location and nature of the abnormal EEG activity.[5]

Brain Injury

Brain injury can affect the EEG in different ways. Damage resulting in death of cortical neurons can lead to diminished amplitudes across the whole EEG spectrum. Damage to parts of the brain that are normally in communication with cortical areas can show up as increased delta (or theta or even alpha) activity in those areas.

Brain damage can often be seen in structural brain scans such as MRI, but not always. Anoxia (oxygen starvation) would not produce structural damage, but might show up in the EEG as prominent slow wave rhythms (frequencies in the delta, theta or alpha ranges). Coma is often characterized by abnormal slow EEG rhythms.[6]

ADD

Attention Deficit Disorder (ADD) has been shown to have real neurological roots. The part of the brain behind the forehead - the Prefrontal Cortex - is known to be underactive in ADD sufferers. The Prefrontal Cortex is the brain’s “executive control”. It’s responsible for purposeful behaviour - making plans and decisions, and also paying attention and keeping on track with a task - precisely the skills that ADD sufferers have difficulty with. Normally the Prefrontal Cortex would become more active when you engage in a demanding mental task, but often in the ADD brain the reverse happens.[7]

In terms of the EEG, ADD can manifest in different ways. Most commonly we see an excess of slow wave activity in the frontal regions of the brain - either theta or alpha. In other cases there is an excess of high-frequency beta activity - these cases tend to show hyperactivity in addition to attention problems.

Depression

Another role of the Prefrontal Cortex is to inhibit activity in other brain regions associated with emotions - in other words in keeps emotions in check. As with ADD, it is often found that the depressive Prefrontal Cortex is underactive.[8]

In the EEG, depression may manifest in a number of ways: [9]

i A relative excess of alpha and/or theta in the frontal regions - perhaps even a reversal of the normal front to back alpha asymmetry mentioned above.

ii Alpha may be slower (i.e. lower frequency) compared to the non-depressed brain.

iii Often there is a preponderance of alpha activity in the right side of Prefrontal Cortex - this is a reversal of the normal asymmetry mentioned earlier.[10]

Anxiety

As with depression, anxiety can manifest in the EEG in a number of ways: [11]

i Relatively higher amounts of beta (especially high frequency beta) across the cortex but especially in the temporal lobes - see figure 7.

ii A reversal of the normal front to back asymmetry in alpha and beta - i.e. more beta in the back of the head.

iii A reversal of the normal left-right asymmetry in beta in the frontal regions - i.e. a predominance of beta on the right.

EEG and Neurofeedback

Neurofeedback attempts to alleviate symptoms by training the subject to influence the EEG. Therapy begins with an assessment of the EEG. The practitioner looks for patterns or markers within the EEG, such as those described above, that correlate with the client's symptoms. Such patterns are the targets for neurofeedback training - that is, the training attempts to "normalise" the EEG. For example, for depression, training may attempt to suppress frontal alpha activity. Neurofeedback has been applied to all the disorders discussed in the previous section, with some success.[12]

It seems that in part neurofeedback works by exercising and strengthening the brain's ability to regulate itself.[13] The ideal goal is not necessarily some particular brain state but flexibility - the ability to reach whatever brain state is most appropriate to the circumstances at hand. No EEG rhythm is good or bad in itself - for example alpha may be conducive to relaxation but not so good at times when you need to concentrate hard.

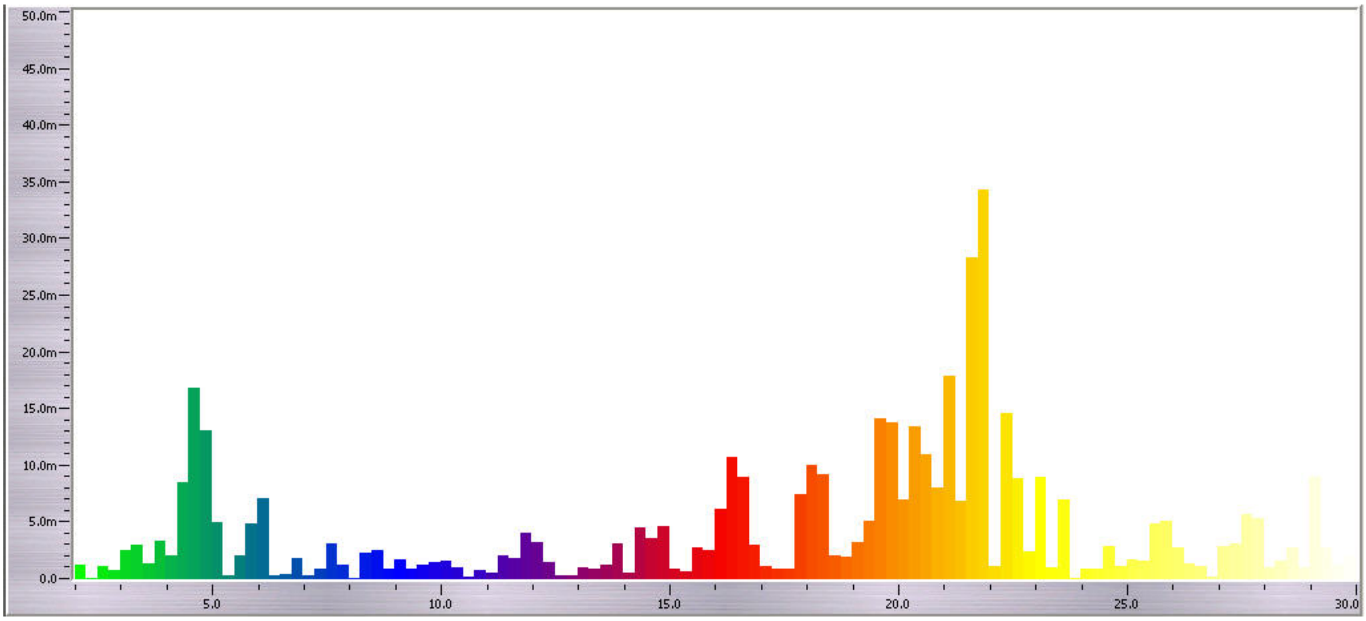

Figure 7: Spectral analysis of EEG recorded above the temporal lobe of an anxious person - note the preponderance of beta acitivity (orange / yellow).

Notes

1 See Thompson & Thompson (2003) for a fuller description of the significance of the frequency bands.

2 See Robert Thatcher, ‘EEG Database-Guided Neurotherapy’, chapter 2 in Evans & Abarbanel (1999).

3 See Bear, et.al. (2001) for an accessible discussion of this topic.

4 Llinas (2002) is a book devoted to this idea.

5 Any textbook on EEG such as Rowan & Tolunsky (2003) will cover the EEG in epilepsy.

6 See Margaret Ayres, Assessing and Treating Open Head Trauma, Coma and Stroke Using Real-Time Digital EEG Neurofeedback’, chapter 9 in Evans and Abarbanel (1999) for a fuller account.

7 Daniel Amen (1998) discusses his research findings for ADD.

8 Amen (2004) discusses the brain in depression at length.

9 Demos (2005) describes EEG correlates of depression.

10 The finding derives largely from the work of Richard Davidson and his team - e.g. See Davidson (1995), or chapter 2 of Cacioppp et.al. (2000).

11 Again see Demos (2005).

12 See the website of the International Society for Neuronal Regulation, www.isnr.org, for a collation of research on neurofeedback.

13 Othmer, S., Othmer, S.F., and Kaiser, D present a model for the efficacy of neurofeedback in Evans and Aberbanel - chapter 11.

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