

SPECIAL ISSUE

Neuronal Dynamics in Relation to Normative Electroencephalography Assessment and Training

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This article presents a comprehensive view of neuronal dynamics and its relationship to normative electroencephalography (EEG) assessment and training. The underlying neuronal processes of excitation and inhibition work in a dynamic balance, to provide cyclical activation and relaxation of neuronal assemblies and their connections. The EEG produced by neuronal assemblies provides a view of the complex processes and interactions between brain locations, with relevance to functional processing. A normative or reference database is essential in identifying targets and ranges for system parameters and determining where a client lies within the range of normal functioning. Normative assessment provides the ability to navigate a multidimensional space that tracks brain function in real time and allows normalization using biofeedback. A case study illustrating brain normalization using multiple Z-scores is presented.

Neuronal Dynamics: An Overview

This report presents a comprehensive view of the role of neuronal dynamics in the production of electroencephalography (EEG) rhythms and in the application of EEG biofeedback to the achievement of brain self-regulation. Drawing from a consideration of the cellular basis of EEG and an understanding of neuronal functions, it is possible to view EEG and EEG operant training as a form of normalization training that emphasizes self-regulation in an objective and scientifically driven approach toward integrated brain function.

It is instructive to begin at a basic level, which is that of individual cortical brain cells. Figure 1 shows a figurative view of layers I to VI of a cortical neuronal assembly. The cells marked P are the pyramidal cells, which are the primary processing elements in the neocortex. This view is the same in various areas of the cortex and is thus applicable whether the cortex is sensory, perceptual, executing motor control, planning, or memory. In all cases, the pyramidal cells are mediated by an extensive network of interneurons (marked H, F, B, N, M, and S), which communicate between and among themselves, as well as with the pyramidal cells. The majority

of interneurons are inhibitory. Without this inhibitory influence, incoming upstream (afferent) neuronal impulses would produce an overabundance of action potentials in the downstream (efferent) neurons, ultimately leading to a chaotic excess of meaningless activity.

The inhibitory interneurons have significant influence and condition the downstream neurons so that action potentials can be produced only as a result of persistent, accumulated afferent signals. By modulating the extent and magnitude of the inhibitory interneuronal activity, the brain can tone down activity, so that the cortex generally has a manageable level of activity, providing useful information processing and control. Another manifestation of essential inhibition is lateral inhibition, in which adjacent neurons have a tendency to inhibit each other's activity. This phenomenon is essential to retaining the acuity of sensory processes, as it prevents the spreading of incoming activity and ensures that a fine level of detail can be preserved as signals are conducted from the peripheral sensory organs, through sensory pathways, into and through the sensory areas of the cortex.

The EEG sees the millivolt-level postsynaptic activity of pyramidal cells in the form of microvolt-level surface potentials that are conducted from the cortex to the scalp via volume conduction (Collura, Luders, & Burgess, 1990). It is when pyramidal cells polarize synchronously that they produce a measurable potential. Generally, the action of these cells is not highly synchronized, so that their external potentials cancel out at the scalp. However, when even a small number of cells polarize in a synchronous fashion, they produce a measurable surface potential. This phenomenon is so extreme that less than 5% of the pyramidal cells are capable, when synchronized, to control more than 95% of the overall EEG. EEG signals are further spread or smeared as they reach the cortex, so that a given surface sensor is able to detect activity not only from the cortex directly below but also from areas distant from the sensor, as shown in Figure 2 (Collura et al., 1990). As a rule of thumb, approximately 50% of the energy detected by a 10-20 site is produced by the cortex lying below the sensor, whereas the other 50% is produced by adjacent, as well as more distant, sites.

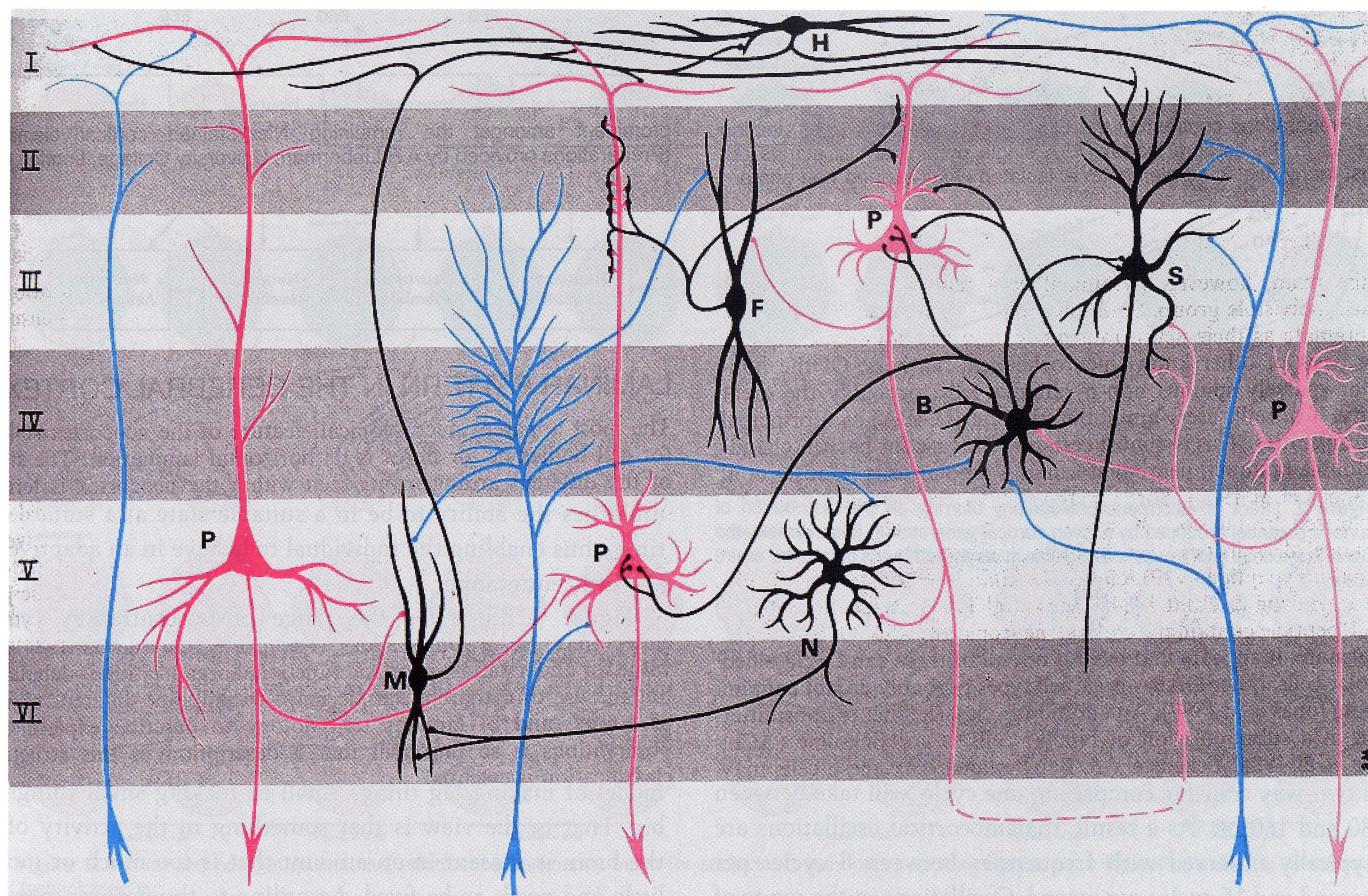


Figure 1. Interior view of a typical neuronal assembly (not to scale). Sponsorship for color figures provided by BrainMaster Technologies, Inc.

The combined activity of multiple neuronal assemblies, their interconnections, and the production of EEG is shown schematically in Figure 3. This simplified representation shows that there are multiple neuronal assemblies, all interconnected in various ways, and all producing their contribution to the overall EEG signal. Whereas the synchronous activity of a given neuronal assembly can produce its portion of the EEG, the connections among neuronal assemblies are responsible for the connectivity measurements (coherence, phase, etc.) that can be measured between sites (Collura, in press).

The Role of Inhibition in Neuronal Dynamics

The brain is a hyperconnected system. Each of the billions of cortical neurons has thousands of connections to other neurons, and these include both short-length and long-length connections. It is possible to connect from a typical cortical neuron to any other cortical neuron in just a few hops. The reason that the brain does not descend into chaos is that the vast preponderance of interneuronal connections are inhibitory, thus holding rampant neuronal firing at bay. It is the inhibitory influences that carve out the fine structure of

connectivity. EEG biofeedback works by allowing the brain to adjust inhibitory connections, to potentiate or to remove connections, and to enable or disable particular locations. It is inhibition that allows structure to emerge in the system. Interneurons inhibit the release of GABA on the part of the pyramidal cells. Inhibitory connections suppress irrelevant communication while preserving relevant communication. Generally, elevated coherence indicates that the system is not inhibiting irrelevant signals sufficiently to sculpt the cortical responses (Siberstein, 2008).

The primary mechanism of neuronal control is inhibition. Whereas most neurons are intrinsically excitable and if left isolated will produce action potentials, the majority of interconnections are inhibitory, thus holding neuronal firing at bay. It is when inhibition is reduced that the neuronal assembly has an increased ability to respond to afferent signals and to participate in rhythmic activity. Thus, the regulation of brain rhythms has, at its core, the control of inhibitory processes, such that the relaxation of inhibition facilitates the production of observable brain rhythms.

This rhythmic activity falls into two broad categories, which are thalamocortical reverberation and corticocortical communication. Thalamocortical reverberation consists of

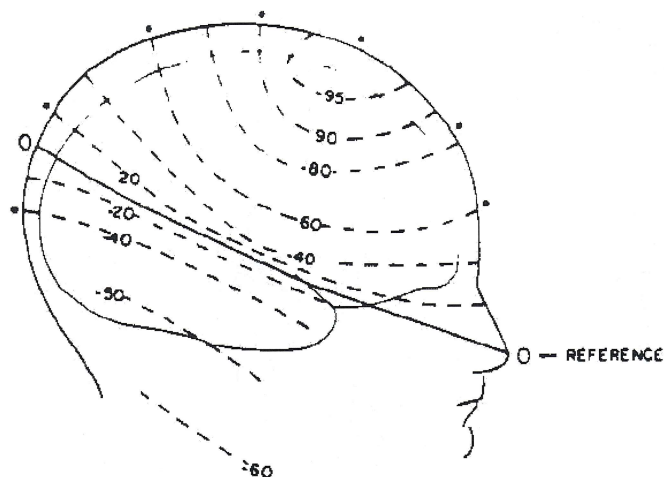


Figure 2. Effect of electroencephalography blurring on the distribution of surface potential produced by a given cortical generator. In this example, the signal is maximal near Fz yet is detectable in varying amounts across the entire scalp.

repetitive activity mediated by a cyclic pattern of signals coming up from the thalamus to the cortex and from the cortex down to the thalamus. Typical delays for thalamocortical signals are between 40 and 80 ms per transmission. Thus, a two-way transfer, comprising one cycle, will take between 80 and 160 ms. As a result, thalamocortical oscillations are typically observed with frequencies between 8 cycles per second and 15 cycles per second. Oscillations in the range of 8 to 12 cycles per second are designated as alpha waves and are evident throughout the brain but are most pronounced in the occipital cortex, particularly when the eyes are closed. Oscillations in the range of 12 to 15 cycles per second are also observed generally but are most pronounced over the motor strip during periods of stillness, and these are designated as the sensorimotor rhythm (SMR).

Overall, the brain is continually modulating and tuning the inhibitory processes within and between neuronal assemblies, and this is a primary method for the control of brain processes in general. Sterman (1996; Sterman, Mann, Kaiser, & Suyenobu, 1994) discovered that the innate control of rhythms, comprising a cycle of concentration and relaxation, is essential for the performance of tasks in an effective and efficient manner. There is a general inhibitory tone that is evident for an individual in the various cortical areas, which contributes to the overall functional orientation. For example, if one presents with an underactive frontal cortex, we generally associate this with a lack of control, inability to plan, and a propensity for impulsive behavior. Superimposed on this general tone is the ability to modulate cortical excitability from moment to moment, as shown by Sterman. This ability to modulate in a manner that is flexible and appropriate

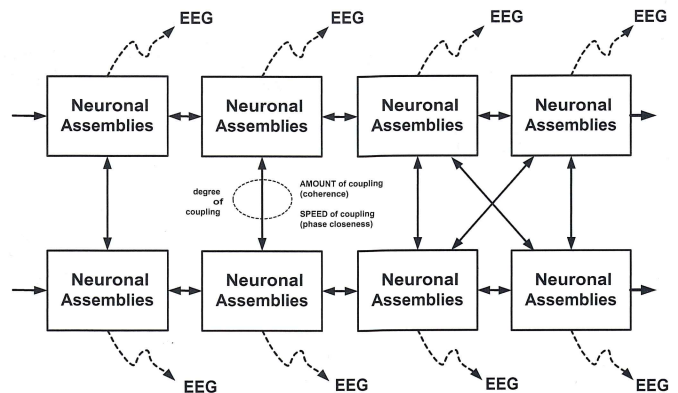


Figure 3. Figurative view of neuronal assemblies, their interconnections, and their production of electroencephalogram.

underlies the ability to be in a suitable state at a suitable time, thus enabling the individual to behave in an adaptive and efficient manner.

Figure 4 illustrates the range of concentration and relaxation along a continuum. At any given instant, any neuronal assembly is predominantly in some location along this continuum.

There is a tendency to view neurofeedback in terms of a model of making big things small or making small things big. That is, the view is that something in the activity of the brain is present in an amount that is too much or too little and needs to be fixed. According to the present view, however, we look at the time behavior of neuronal activity and understand that the traditional amplitude measurements are more of a reflection of how often or how rare a given brain state is, within the context of the overall neuronal time course. Neurofeedback is thus not so much an issue of pushing rhythms up or down but more one of teaching the

The Concentration/Relaxation Cycle and EEG Amplitude/Frequency Changes

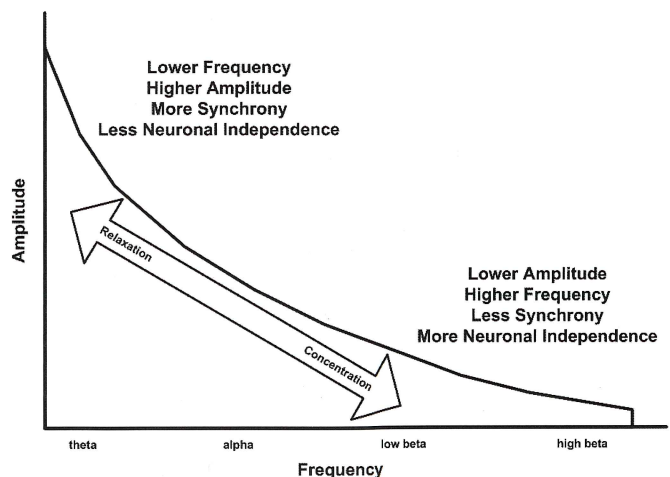


Figure 4. The concentration/relaxation cycle continuum.

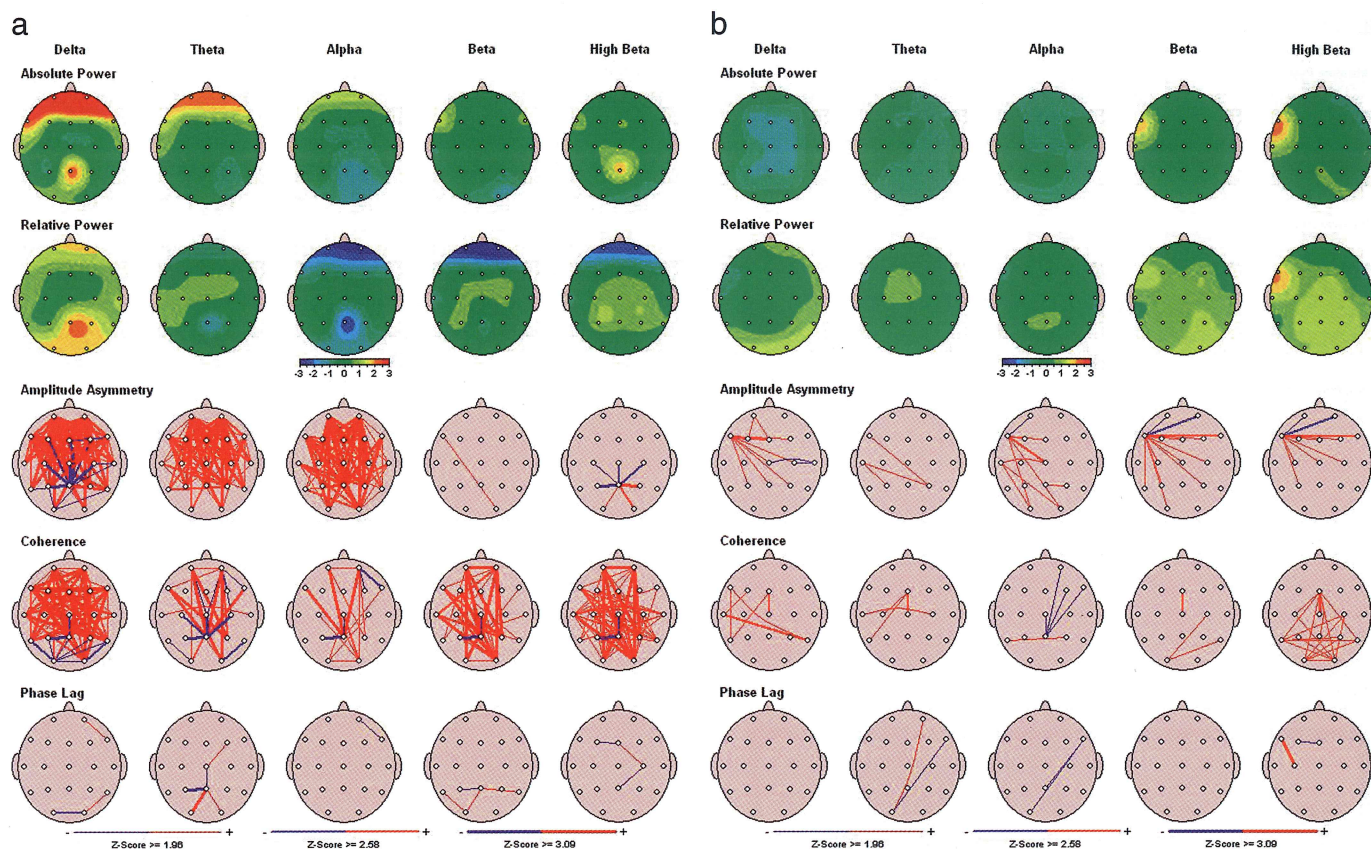


Figure 5. Pre (a) and post (b) quantitative electroencephalography maps for subject SL, eyes open. Sponsorship for color figures provided by BrainMaster Technologies, Inc.

brain to find alternative activation states and to integrate them into its modes of functioning.

Normative assessment is an attempt to understand an individual's brain rhythms in terms of quantity and connectivity, in relation to a population that is regarded as normal or average. It is thus possible to assess the fine-tuning of the brain as a complex system and to understand how well, or how poorly, a given brain corresponds to a normal brain, in terms of these activation and connectivity patterns.

It is possible to see deviations from normal that are not in themselves harmful or detrimental. Some of these fall under the category of peak performance attributes. Others can be viewed as individual differences that are not necessarily related to any clinical or personal complaint. Healthy deviations include nonharmful excesses such as elevated alpha waves or SMR waves, in certain cases. In other cases, elevated alpha can reflect a coping mechanism in cases of chronic anxiety. Similarly, reduced alpha may simply reflect an individual style oriented toward more activation than is typical. However, in cases of chronic pain, reduced alpha may reflect a tendency toward heightened neural tone, indicating an inability to relax and a state of chronic high arousal.

Normalization of the EEG provides the opportunity for the individual to find a more stable neuronal configuration. It does not in itself provide a cure for a disorder. Rather, it allows the brain to find an alternative set of stable dynamics, which the individual can now use in the course of thought and action.

When normalization is appropriate and complete, things that were not targeted can be seen to normalize. However, when normalization is partial, it is possible for the brain to find other avenues to express its dysregulation. This leads to the concept of neuronal hydraulics, which states that if we push on the system without holding sufficient variables constrained, the system may find other outlets, and other dysregulations may express themselves. This is a well-known and documented phenomenon in the pursuit of connectivity training (Walker, Kozlowski, & Lawson, 2005).

In neurofeedback training, we provide the brain with the opportunity for change, and the brain works out the internal details using its own mechanisms. We may be presented with a brain that has various stress orientations and provide the information that helps is to find a more relaxed and appropriate set of states. The brain spontaneously seeks its own stability and homeostasis, subject to the internal and external information with which it can work. Whereas a given individual may have cortical locations that are underaroused,

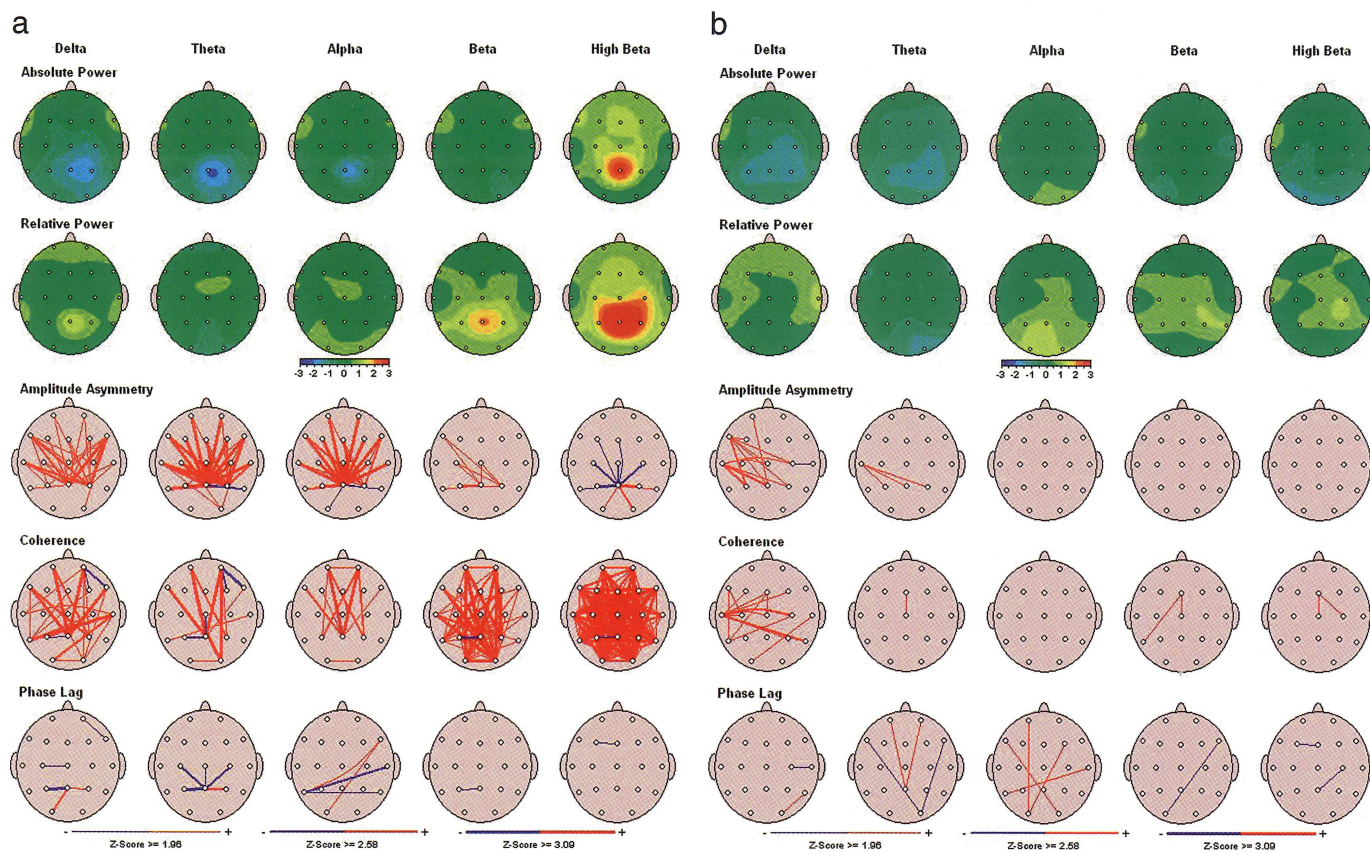


Figure 6. Pre (a) and post (b) quantitative electroencephalography maps for subject SL, eyes closed. Sponsorship for color figures provided by BrainMaster Technologies, Inc.

overaroused, underconnected, or overconnected, the brain copes with its condition by trying to do the best job of regulating states and behavior, subject to the constraints of neuronal dynamics and change. The things we view as symptoms are emergent properties of a system that is in what it regards as an optimal state, given its past history and physical resources. Neurofeedback provides the ability to change by providing additional information, thus altering the experiential framework within which the brain can seek stable states of operation.

Z-Score Neurofeedback

One approach to providing the brain with the information it needs to self-regulate is called Z-score neurofeedback. Z-score neurofeedback uses the normative data from a specific database to provide real-time feedback of a variety of comparisons of current brain amplitudes at various frequencies, along with coherence and phase computations among multiple sites with normative values. Any variable that differs significantly from the normative database will be highlighted instantaneously. Z-scores are deviation scores, valued in terms of standard deviations, so that a Z-score of 1 indicates that this variable is 1 standard deviation above the normative value. The actual feedback can be an auditory tone

or a visual animation and may represent a single Z-score value, such as Beta amplitude at Cz, or may be a composite of many Z-scores representing multiple sites, amplitudes, coherences, and phase relationships. The discussion of Z-score neurofeedback in the following is based on the current Brainmaster™ Z-score neurofeedback software.

The quantitative EEG (QEEG) pre- and postanalyses shown in Figure 5 illustrates the effects of a comprehensive Z-score-based EEG neurofeedback training on an individual diagnosed with attention-deficit hyperactivity disorder, behavior problems, and aggressive tendencies (Collura, Thatcher, Smith, Lambos, & Stark, in press). The origin of the disorder can be seen in EEG characteristics including excessive frontal slowing, a deactivated posterior cingulate gyrus, and widespread connectivity abnormalities. The subject was treated with 21 sessions of training using sound and video feedback, which was controlled by a computed metric that incorporated 248 different EEG variables in real time and provided moment-to-moment proportional feedback that increased as the EEG normalized.

The QEEGs in Figure 6 are taken from the same subject but are taken in the eyes-closed condition. Note that the training was done with eyes open. This shows that the EEG feedback training is capable of addressing problems that are

differently expressed yet reveal normalization nonetheless. In other words, the training in the eyes-closed condition also produces significant changes evident in the eyes-open QEEG. Training at specific sites also typically generalizes to normalize QEEG values at other sites.

This example illustrates the role of a variety of brain regulatory dysfunctions on the EEG and on the behavior of the patient. Moreover, when the EEG abnormalities are addressed using a comprehensive feedback program that facilitates self-regulation, the brain is capable of achieving appropriate levels of activation, relaxation, and connectivity as revealed by the EEG.

Conclusion

In summary, normative EEG biofeedback provides the brain with an opportunity to explore alternative systems of activation and connectivity. We do not subscribe to a philosophy of pushing the brain toward the norm, as the primary mechanism of change. Rather, the brain will spontaneously seek states of minimum energy and maximum stability, subject to the environment and the experiences it provides. EEG biofeedback provides an alternative environment that include neuronavigational aids coupled with a means for learning via operant conditioning. Based on the experience of this navigational information and its own priorities, the brain is then able to discover and retain new ways of functioning.

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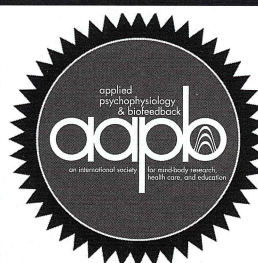
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