CHAPTER 5

EEG biofeedback training using live Z-scores and a normative database

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I. INTRODUCTION

This chapter discusses the technical background, and initial clinical results obtained in an implementation of live Z-score-based training (LZT) in an EEG biofeedback system. This approach makes it possible to compute, view, and process normative Z-scores in real-time as a fundamental element of EEG biofeedback. While employing the same type of database as conventional QEEG post-processing software, LZT software is configured to produce results in real-time, suiting it to live assessment and training, rather than solely for analysis and review.

The Z-scores described here are based upon a published database, and computed using the same software code that exists in the analysis software, when used in "dynamic JTFA" mode. The database includes over 600 people, age 2 to 82. The system computes real-time Z-scores using JTFA (joint time frequency analysis) rather than using the FFT (fast fourier transform), which is more commonly used for obtaining post-processed results. As a result, Z-scores are available instantaneously, without windowing delays, and can be used to provide real-time information.

Live Z-scores can be used either for live assessment or for feedback training, depending on how the system is configured and used. When used for assessment, live Z-scores can be viewed during data acquisition, and can also be recorded and reviewed, as a simple, fast assessment. When used for training, the Z-scores must be integrated in some fashion into the feedback design, so that they are used to control displays, sounds, or other information, for purposes of operant conditioning and related learning paradigms.

When used for training, the targeting method is important. There is a considerable range of possible approaches, ranging from the obvious use of a single Z-score as a training target, to more complex approaches that combine Z-scores in various ways, to produce more comprehensive training information. Upon first consideration, Z-scores can be used simply as an alternative means to produce a single target, for example to train a particular amplitude, amplitude ratio, or coherence value. While the core Z-score software in different systems may be uniform, there are further refinements regarding the incorporation into useful feedback including visual, auditory, or vibrotactile information. It is in this level of integration and system design that much of the "art" of Z-score biofeedback resides.

When combining Z-scores, one might initially consider presenting multiple targets to the trainee, and instructing them to train using several bar graphs, or similar displays. This may lead to complexity, and difficulty in presenting a simple and intuitive display. However, it is also possible to combine Z-scores internally to the software, and to present a simple feedback display to the trainee, such as a single graph or animation, that reflects the combined results. When doing so, we may have concern that the individual needs to "sort it out" or somehow "figure out" what is expected. However, this tendency to complicate both the system and the trainee's task may be unnecessary.

In the case studies shown here, Z-score training was accomplished with two or four channels of EEG. This provides an enormous amount of potential information in the form of Z-scores, and begs for a way to manage it. Protocols and entire approaches were innovated on-the-fly, as clinical changes and EEG observations motivated increasingly integrated yet simple-to-use protocol designs. We have found that it is possible to use combined Z-scores for training, and that up to 248 such scores can be used simultaneously with four channels, and with a simple and intuitive user interface. Even though the feedback may be controlled by an exceedingly complex internal design, when simple and intuitive feedback displays are presented, the trainee's brain does indeed appear capable of "sorting out" the targeted brain state, quickly, and efficiently. Key issues here relate to the methods for selection and decision-making relative to a plethora of Z-scores, and the reporting of meaningful results and statistics.

When inspecting individual live Z-scores, it is observed that their typical values are not the same as those observed when using post-processed QEEG results, as is explained in technical detail below. Initially, this was a cause for confusion and concern, until the underlying reasons are understood. To pursue this, let us use height as an example, rather than an EEG metric. To view a live Z-score in this case is analogous to watching an individual in action, for example playing a game, or working, in contrast to standing still. Post-processed Z-scores may be compared to taking single height measurements of individuals standing still, and using the data to produce a population statistic. The population statistics of static height might typically produce, for adult males, for example, a mean of 5 feet 10 inches, and a standard deviation of 2–3 inches. Thus, if an individual has a standing height

of 6 feet 3 inches, that would be considered tall, perhaps more than 3 standard deviations out, and hence produce a Z-score of 3 or more.

However, if individuals are working or playing, for example jumping up and down, then the range is considerably larger. For anyone playing basketball to be 6 feet 3 inches above the ground is not so unusual, and may produce a Z-score of 2 or even less. Based upon this consideration, it can be understood that, if an individual has a conventional QEEG Z-score of 3 for a particular parameter (say absolute power), then when they are evaluated using live Z-scores, their score may be more like 2, or even less. This is not a problem or defect in the system, it is a natural consequence of watching a live statistic, versus a static statistic.

Despite this difference in the quantitative characteristics of live versus static Z-scores, LZT can be used as a valid and effective training paradigm, and is consistent with established QEEG-based practice. Live Z-scores can be used to train a combination of variables including absolute and relative power, power ratios, coherence, phase, and asymmetry. When used in this manner, the system is no longer targeting just a single variable or attribute. Rather, the possibility arises of training the brain in a complex multidimensional manner, so that it learns a comprehensive brain state. For example, if an individual learns to self-regulate along the concentration/relaxation dimension, but also learns to regulate the amplitude relationship between different frequency component bands, or between different sites, or the connectivity between sites, then a more complex target is produced. This may be thought of as moving the biofeedback training in the direction of a complex task such as riding a bicycle or reading a book, rather than simply "bench pressing" a single parameter, such as theta amplitude, up or down.

When viewed in this way, live Z-score training is not simply a convenience or a method for establishing training targets. It is a way to comprehensively define a brain state, and to train the individual to find and sustain it. More significantly, it provides an entirely new conceptual framework for designing protocols. It amplifies the value of the QEEG, and the QEEG significantly informs the use of Z-score training. LZT can be used as a combination GPS and navigator for the brain. It guides the trainee in a set of complex relationships including absolute and relative neuronal activation, as well as neuronal connectivity and interoperation. Rather than simply instructing the trainee to "make this larger" or "do more of that," it provides a comprehensive feedback reflecting a balanced, coordinated set of neuronal activities and relationships.

Nor is LZT limited to a strategy or "training to the norm." With LZT, we can also choose to up-train or down-train any components we like, including combinations of components, or relationships between components; so we can train to a Z-score of -2 or -3, or $+2$ or $+3$, or even $+6$ if we choose. The use of Z-score training does not dictate the targets used to create contingent feedback; rather, it casts targets in a new dimension. It is also important to emphasize that using Z-scores does not automatically relegate us to the domain of normalizing the EEG, although that is certainly an obvious and valuable option. For example, simultaneously

normalizing multiple coherences in a single band between F3 and P3 is a promising direction for those with language challenges. At the same time, we can tweak any metrics we like up or down, based on judicious choices and stated goals. The use of Z-scores really provides an alternative to the concept of thresholding, and provides us with "portals" through which we can shoot the metrics, based on our own needs and persuasions.

LZT can also be combined with other protocol approaches, if the system and software will allow it. For example, the situation may arise in which conventional alpha or SMR enhancement training is desired, but it is also desired to maintain a normal connectivity metric. In other words, it may be desirable to train an individual to produce 12–15 Hz in a particular area, but to get rewards only insofar as the connectivity between certain areas is normal. As another example, one may wish to encourage synchronous alpha across the head, while at the same time ensuring that a collection of Z-scores is in the normal range.

When employing LZT, the conceptual and quantitative framework underlying the EEG training may differ from that commonly encountered, while at the same time, certain familiar elements may remain. For example, the size of the Z-score targets, expressed in "standard deviations," may replace the concept of threshold in conventional training. When multiple Z-scores are used, then the number of Z-scores that are within a certain target range may become a training goal, replacing the traditional "how big" or "how much" of some metric such as amplitude or coherence.

Despite this shift in thinking, the ultimate performance of feedback and training can be achieved without any change in the trainee's task or conceptual load. For example, it is possible to convert the results of multiple Z-scores into a single metric, and to train on that metric using a conventional trend line, bar graph, animation, or sound. In the clinical studies described here, one such approach has been to use a large number of Z-scores, possibly all that are available, to set a particular target size, and to use the number of achieved targets as the training variable, by watching that quantity on a graph, and using the current score as a parameter to control sound and visual feedback. Despite this rather radical shift in thinking, it is still possible to use a familiar feedback mechanism so that the trainee is not aware of any change in the underpinnings, and experiences only a change in the exact brain state(s) that are accompanied by reward feedback.

Some comments are in order regarding the overall role of LZT in the EEG biofeedback arsenal. One regards the idea that LZT training somehow obviates the need for the QEEG. The thinking is that, since LZT incorporates normative scores into its operation, there is less (or no) need to perform a full-head assessment. We do not agree with this point of view. The conventional QEEG remains an essential tool for assessing the overall condition of the trainee, and to plan interventions. There may be situations in which simply training to the norm may not be indicated. In any case, it is essential that the therapist understands the anticipated changes, and is prepared to deal with them. For example, a client may be expected to change as a result of feedback training, and it is the clinical training and experience of the clinician that will be needed to deal with these changes.

The second consideration is how LZT impacts the need for the clinician. We do not see LZT in any way reducing the role of the clinician, any more than an autopilot in a commercial airliner obviates the need for a trained, experienced pilot, or a laser-guided laparoscopic surgery obviates the need for a good surgeon. LZT ultimately provides a new targeting method, and a new way to teach the brain to achieve desired states. However, the core goal remains to treat an individual, which is the role of the clinician. Someone is needed to determine optimal placement, protocols, and clinical actions, and to oversee the process.

Two additional comments are in order. One has to do with what LZT can do in regard to peak performance and mental fitness, and the other has to do with how it relates to "normal" individuals.

There has been concern expressed regarding the possible effects of LZT on otherwise "normal" people. It has been posited that LZT training may "dumb down" individuals, by training them to a normal, hence mediocre, population. Ultimately, this is something that only experience can reveal. We have seen various reactions in this situation.

We have seen cases in which a normal or high-performing individual actually finds LZT training beneficial, pleasant, relaxing, and stimulating. In one situation, we observed an individual (a workshop attendee) who showed a slightly high C4 SMR signal, as well as mild hypo-coherence between C3 and C4. This may be interpreted as a "high-performance" EEG, since C4 SMR training is well recognized as a beneficial treatment, and also a mild amount of inter-hemispheric independence is not necessarily a bad trait. When given a comprehensive Z-score training, this individual reported benefits including being more relaxed, yet feeling energized. These are consistent with the fact that she received two components of training via LZT. The first was a mild "squash" training on the motor strip in the 12–15 Hz range (energizing), as well as some coherence up-training on the motor strip (relaxing).

In another situation, however, we observed another workshop attendee who showed more markedly pronounced motor strip SMR, and further informed us that he had developed the habit of sitting very still, and attending to his clients. When presented with LZT training, he simply reported that he did not like it. This is consistent with findings that individuals who have their alpha or SMR "where they like it" do not respond well to training that attempts to alter it. In summary, LZT training may be fine for certain individual from the normal spectrum, and may be undesirable for others.

With regard to peak performance and related issues, it should be noted that LZT does not automatically target the attributes typically used in this realm. For example, one common training approach is to encourage global alpha synchrony. While LZT could be used to target this type of EEG change, if one wants to increase alpha synchrony there are more direct methods to do so. LZT might be of value in monitoring such training, but is not specifically beneficial when the goal is simply to "make more alpha." Another peak-performance paradigm, the "squash" protocol, is also not specifically targeted using LZT. In this case, the

goal is to acquaint the trainee with a "low voltage fast" (activated) state of EEG, in contrast to "high voltage slow" (relaxed) state. Again, we do not see LZT in any way replacing this approach, although it can provide a valuable adjunct. A third form of training that is not addressed by LZT is alpha/theta training, in which the goal is to achieve an altered, hypnogogic state of consciousness, useful for therapeutic purposes.

When put in context, LZT is a significant advance, and may prove revolutionary. At the core, it remains a form of operant conditioning, which teaches the brain to exercise the cycle of concentration and relaxation, in a systematic and defined manner. What has changed is the source of information informing the feedback, providing a biofeedback version of the "$1000 golf lesson." The following technical details and clinical case studies provide insight into its clinical utility, and possible ultimate effectiveness.

II. DESIGN OF THE INSTANTANEOUS Z-SCORE NORMATIVE DATABASE

The number of subjects (N = 625), selection criteria, age range (2 months to 82 years), cross-validation tests, demographics, and other details of the Z-score normative database have been published, and are recommended reading for those interested in more detail than is briefly reviewed in this chapter (see Thatcher *et al.*, 1983, 1986, 1987; Wolf and Thatcher, 1990; Thatcher, 1998, 1999; Thatcher *et al.*, 2003). There are four basic concepts used in the design of Z-score biofeedback as described below:

A. Use of Gaussian probabilities to identify "de-regulation" in the brain

The fundamental design concepts of Z-score biofeedback were first introduced by Thatcher (1998, 1999, 2000a, 2000b, 2000c). The central idea of the instantaneous Z-score is the application of the mathematical Gaussian curve or 'bell shaped' curve by which probabilities can be estimated using the auto and cross-spectrum of the electroencephalogram (EEG) in order to identify brain regions that are deregulated and depart from expected values. Linkage of symptoms and complaints to functional localization in the brain is best achieved by the use of a minimum of 19-channel EEG evaluation so that current source density and LORETA source localization can be computed. Once the linkage is made, then an individualized Z-score protocol can be devised. However, in order to make a linkage to symptoms, an accurate statistical inference must be made using the Gaussian distribution.

The Gaussian distribution is a fundamental distribution that is used throughout science, for example the Schrodinger wave equation in Quantum mechanics uses the Gaussian distribution as basis functions (Robinett, 1997). The application of the EEG to the concept of the Gaussian distribution requires the use of standard mathematical transforms by which all statistical distributions can be transformed to a Gaussian distribution (Box and Cox, 1964). In the case of the EEG, transforms such as the square root, cube root; $\log_{10}$, Box–Cox, etc. are applied to the power spectrum of the digital time series in order to approximate a normal distribution (Gasser *et al.* 1988; John *et al.* 1987, 1988; Duffy *et al.* 1994; Thatcher *et al.* 2003, 2005a, 2005b). The choice of the exact transform depends on the accuracy of the approximate match to a Gaussian distribution. The fact that accuracies of 95–99% match to a Gaussian are commonly published in the EEG literature encouraged Thatcher and colleagues to develop and test the Z-score biofeedback program.

B. Application of Gaussian probability distributions to instantaneous Z-score biofeedback, and why JTFA Z-scores are smaller than FFT Z-scores

The second design concept is the application of the Gaussian distribution to averaged "instantaneous" time domain spectral measures from groups of normal subjects, and then to cross-validate the means and standard deviations for each subject for each instant of time (Thatcher, 1998, 1999, 2000a, 2000b). The cross-validation is directly related to the variance of the distribution (Thatcher *et al.*, 2003, 2005a, 2005b). However, in order to achieve a representative Gaussian distribution it is necessary to include two major categories of statistical variance:

1. The moment-to-moment variance or within session variance.
2. Between subject variance across an age group.

In the case of the Fast Fourier Transform (FFT) there is a single "integral" of the power spectrum for each subject and each frequency and, therefore, there is only between subject variance in normative databases that use non-instantaneous analyses such as the FFT. Thus, there is a fundamental and important difference between an instantaneous Z-score and an integrated FFT Z-score, with the former having two sources of variance while the latter has only one source of variance. Figure 5.1 illustrates the relationship between an FFT-based normative database versus an "instantaneous" or joint time frequency analysis (JTFA) database, such as used for the computation of instantaneous Z-scores.

C. Simplification and standardization

The third design concept is simplification and standardization of EEG biofeedback by the application of basic science. Simplification is achieved by the use of a single

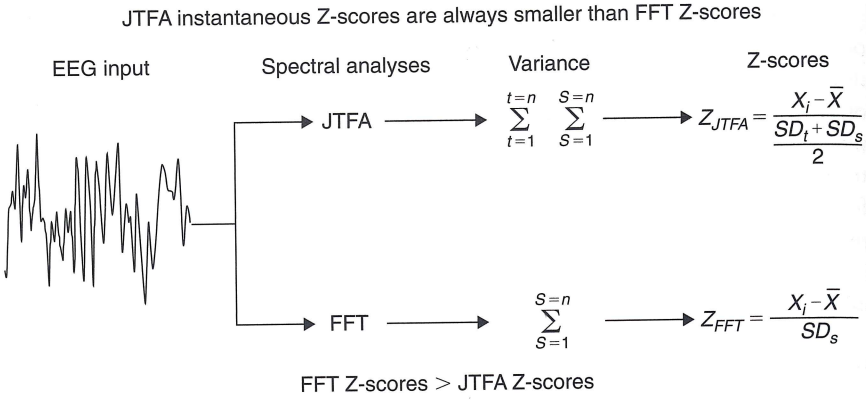

FIGURE 5.1 JTFA normative databases are instantaneous and include within session variance plus between subject variance. In contrast, FFT normative data only contains between subject variance. t = time, s = subjects and SD_t = standard deviation for the within session and SD_s = standard deviation between subjects. Thus FFT Z-scores are larger than JTFA Z-scores, and a ratio of 2:1 is not uncommon. (From Thatcher *et al.*, www.appliedneuroscience.com)

metric, namely, the metric of the "Z-score" for widely diverse measures such as power, coherence, and phase delays. Standardization is also achieved by EEG amplifier matching of the frequency response of the normative database amplifiers to the frequency characteristics of the EEG amplifiers used to acquire a comparison subject's EEG time series.

D. Individualized EEG biofeedback protocols

A fourth and intertwined clinical concept in the design of Z-score biofeedback is "individualized" EEG biofeedback, and non-protocol drive EEG biofeedback. The idea of linking patient symptoms and complaints to functional localization in the brain as evidenced by "deregulation" of neural populations is fundamental to individualized biofeedback. For example, deregulation is recognized by significantly elevated or reduced power or network measures such as coherence and phase within regions of the brain that sub-serve particular functions that can be linked to the patient's symptoms and complaints. The use of Z-scores for biofeedback is designed to "re-regulate" or "optimize" the homeostasis, neural excitability, and network connectivity in particular regions of the brain. The functional localization and linkage to symptoms is based on modern knowledge of brain function as measured by fMRI, PET, penetrating head wounds, strokes and other neurological evidence acquired over the last two centuries (see Heilman and Valenstein, 1993; Braxis *et al.*, 2007; the Human Brain Mapping database of functional localization at: http://hendrix.imm.dtu.dk/services/jerne/brede/index_ext_roots.html).

Thus, the false concern that Z-score biofeedback will make exceptional people dull and an average individual a genius is misplaced. The concept is to link symptoms and complaints, and then monitor improvement or symptom reduction during the course of treatment. For peak-performance applications, a careful inventory of the client's personality style, self-assessment of weaknesses and strengths, and identification of the client's specific areas that they wish to improve must be obtained before application of Z-score biofeedback. Then, the practitioner attempts to link the client's identification of areas of weakness that they want improved to functional localization as expressed by "deregulation" of deviant neural activity that may be subject to change.

As mentioned previously, the instantaneous Z-scores are much smaller than the FFT Z-scores in NeuroGuide™ which uses the same subjects for the normative database. Smaller Z-scores when using the instantaneous Z-scores is expected. One should not be surprised by a 50% reduction in JTFA Z-scores in comparison to FFT Z-scores, and this is why it is best to first use 19-channel EEG measures and the highly stable FFT Z-scores to link symptoms to functional localization in the brain to the extent possible. Then use the Z-score program inside of NeuroGuide™ to evaluate the patient's instantaneous Z-scores in preparation before the biofeedback procedure begins. This will allow one to obtain a unique picture of the EEG instantaneous Z-scores of each unique patient prior to beginning Z-score biofeedback.

The clinician must be trained to select which Z-scores best match the patient's symptoms and complaints. A general rule is that the choice of Z-scores to use for biofeedback depends on two factors obtained using a full 19-channel EEG analysis: 1) scalp location(s) and, 2) magnitude of the Z-scores. Deregulation by hyperpolarization produces slowing in the EEG, and deregulation due to reduced inhibition produces deviations at higher frequencies. The direction of the Z-score is much less important than the location(s) of the deviant Z-scores, and the linkage to the patient's symptoms and complaints.

It is possible to review a patient's EEG prior to designing a Z-score biofeedback protocol. The Z-score biofeedback program inside of NeuroGuide™ is the same program as used by BrainMaster and other EEG system providers.

III. INSTANTANEOUS Z-SCORES ACCESSED FROM INSIDE OF NEUROGUIDE™

Figure 5.2 is an example of the instantaneous Z-score screen inside of NeuroGuide™ while the instantaneous Z-scores are being reviewed.

A P4 and C4 theta and delta deviation from normal is evident as well as bilateral occipital delta deviations from normal. There is diminished alpha and theta in the instantaneous Z-scores, but on the average the dynamic FFT provides a much clearer picture of the right parietal and right central Z-scores. For illustration

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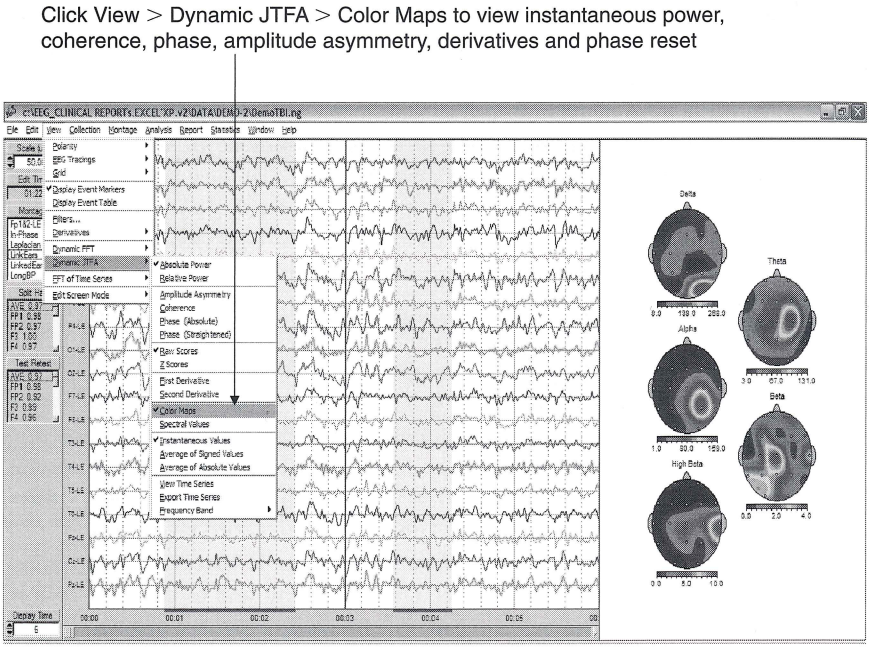


FIGURE 5.2 Screen capture from NeuroGuide™ in the Demo mode from a patient with right parietal and right central injury. Instantaneous Z-scores are on the right; EEG traces are on the left. Depress the left mouse button and move the mouse over the traces. Move the mouse to the right border and watch a movie of the dynamic Z-scores. Download the free NeuroGuide™ Demo at www.appliedneuroscience.com (see color plate)

purposes only, a biofeedback protocol would be to reward Z-score values less than and greater than 2 standard deviations in the theta frequency band in P4 and C4; most of the feedback rewards will automatically occur in the delta and theta frequency band. As mentioned previously, Fig. 5.2 is an example of an individualized Z-score biofeedback procedure after reviewing the patent's EEG using the same instantaneous Z-score program that is employed in the live Z-score DLL and incorporated into EEG biofeedback systems.

IV. IMPLEMENTATION OF THE Z-SCORE BIOFEEDBACK

Step one is to compute means and standard deviations of instantaneous absolute power, relative power, power ratios, coherence, phase differences, and amplitude asymmetries on selected age groups of normal subjects from the 19-channel 10/20 electrode locations using the within session and between session variance as

described previously. The inclusion/exclusion criteria, number of subjects, number of subjects per age group, cross-validation procedures, and other details of the means and standard deviation computations are published (Thatcher *et al*, 1987; 2003).

Step two is to develop a dynamic link library (DLL) that can be distributed to EEG biofeedback system manufacturers, which allows the manufacturers to integrate the instantaneous Z-scores inside of their already existing software environments. The DLL involves only four command lines of code, and is designed for software developments to easily implement the instantaneous Z-scores by passing raw digital data to the DLL and then organizing the Z-scores that are returned in less than one microsecond. This rapid analysis and return of Z-scores is essential for timely feedback when specific EEG features are measured by the complex demodulation JTFA operating inside of the DLL.

V. JTFA COMPLEX DEMODULATION COMPUTATIONS

The mathematical details of complex demodulation used to compute the instantaneous Z-scores as contained in the Applied Neuroscience, Inc. "DLL" are published in Otnes and Enochson (1977), Granger and Hatanaka (1964), Bloomfield (2000), and Thatcher *et al.* (2008). Complex demodulation is a time domain digital method of spectral analysis whereas the fast fourier transform (FFT) is a frequency domain method. These two methods are related by the fact they both involve sines and cosines; both operate in the complex domain, and in this way represent the same mathematical descriptions of the power spectrum.

The advantage of complex demodulation is that it is a time domain method and less sensitive to artifact, and it does not require windowing nor even integers of the power of 2 as does the FFT. The FFT integrates power in a frequency band over the entire epoch length and requires windowing functions, which can dramatically affect the power values, whereas, as mentioned previously, complex demodulation does not require windowing (Otnes and Enochson, 1972). Complex demodulation was computed for the linked ears and eyes-open and eyes-closed conditions for all 625 subjects in the normative database.

Figure 5.3 is an illustration of the method of complex demodulation for the computation of power, coherence and phase. The mathematical details are in Thatcher *et al.*, 2007.

VI. Z-SCORES AND QEEG NORMATIVE DATABASES

Matousek and Petersen (1973) computed means and standard deviations in one-year age groups, and were the first to use Z-scores to compare an individual to

TABLE 5.1 Center frequencies and bandwidths of the Z-score biofeedback DLL and NeuroGuide

	Center Frequency	Band Width
Delta	2.5 Hz	1–4 Hz
Theta	6.0 Hz	4–8 Hz
Alpha	10.0 Hz	8–12 Hz
Beta	18.5 Hz	12–25 Hz
Hi-Beta	27.5 Hz	25–30 Hz
Beta 1	13.5 Hz	12–15 Hz
Beta 2	16.5 Hz	15–18 Hz
Beta 3	21.5 Hz	18–25 Hz
Alpha 1	9.0 Hz	8–10 Hz
Alpha 2	11.0 Hz	10–12 Hz
Gamma 1*	FFT only	30–35 Hz
Gamma 2*	FFT only	35–40 Hz
Gamma 3*	FFT only	40–50 Hz

* = NeuroGuide only

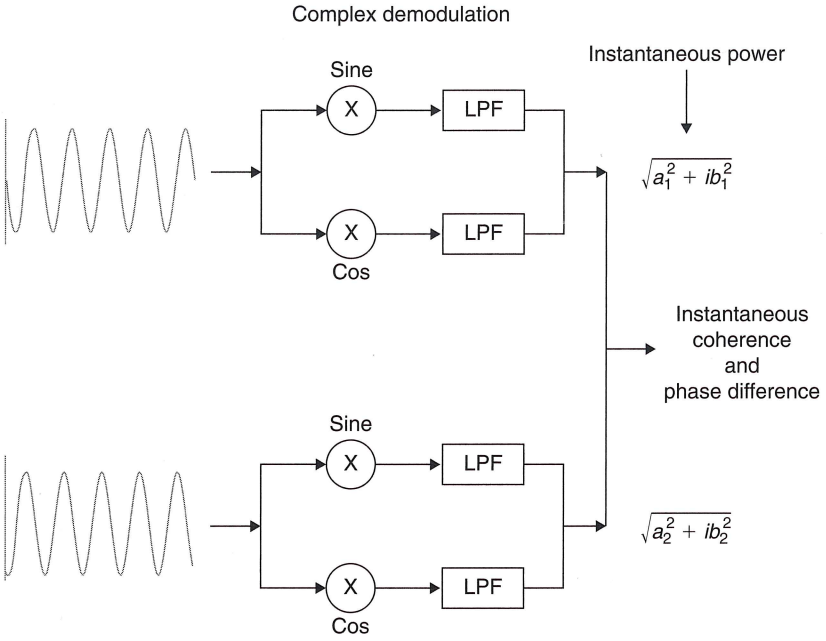


FIGURE 5.3 Diagram of complex demodulation. Left is a sine wave as input, which is multiplied by the sine and cosine waves at the center frequency of a given frequency band as described in Table 5.1, which transforms the digital time series to the complex plane. A 6th order Butterworth low-pass filter is used to shift the frequency to zero where power at the center frequency is then calculated using the Pythagorean theorem. Complex numbers are then used to compute coherence and phase as described in Appendix, section 4.0. (From Thatcher *et al.*, 2007, www.appliedneuroscience.com)

the normative database means and standard deviations. The Z-score is an excellent statistic defined as the difference between the value from an individual and the mean of the population divided by the standard deviation of the population or

$$Z = \frac{x_i - \bar{X}}{SD}$$

John and collegues (John *et al.*, 1987) expanded on the use of the Z-score for clinical evaluation, including the use of multivariate measures such as the Mahalanobis distance metric. A direct normalization of the Gaussian distribution using Z-scores is useful in comparing individuals to a QEEG normative database. That is, the standard score form of the Gaussian is where the mean = 0 and standard deviation = 1 or, by substitution into the Gaussian equation for a bell shaped curve, then

$$Y = \frac{1}{\sqrt{2\pi}} e^{-z2/2}$$

where Y = Gaussian distribution and the Z-score is a deviation in standard deviation units measured along the baseline of the Gaussian curve from a mean of 0 and a standard deviation = 1, with deviations to the right of the mean being positive and those to the left negative. By substituting different values of Z then different values of Y can be calculated. For example, when Z = 0, Y = 0.3989 or, in other words, the height of the curve at the mean of the normal distribution in standard-score form is given by the number 0.3989. For purposes of assessing deviation from normal, the values of Z above and below the mean, which include 95% of the area of the Gaussian, are often used as a level of confidence necessary to minimize Type I and Type II errors. The standard-score equation is also used to cross-validate a normative database, which again emphasizes the importance of approximation to a Gaussian for any normative QEEG database.

A. Standardization by amplifier matching and QEEG normative databases

Surprisingly, matching of amplifier frequency characteristics as a standard was largely neglected during much of the history of QEEG normative databases. In 1982 to 1987 E. Roy John and colleagues formed a consortium of universities and medical schools that were using QEEG who met several times over a few years; the consortium was one of the supporters of the edited volume by John titled "Machinery of the Mind" (John, 1990). One of the important issues consistently raised at the consortium meetings was the need for "standardization." In the 1980s it was technically difficult to match different EEG systems because of

the infantile development of analysis software. This forced most QEEG users to use relative power, because absolute power was not comparable between different EEG machines. There was no frequency response standardization between different EEG machines, and thus there was no cross-platform standardization of QEEG.

It was not until the mid 1990s that computer speed and software development made amplifier matching and normative database amplifier equilibration a possibility. The first use of standardized matching of amplifiers was to the University of Maryland (UM) database (Thatcher *et al.*, 2003). The procedure involved injecting microvolt calibration sine waves into the input of amplifiers of different EEG machines, and then injecting the same microvolt signals into the normative database amplifiers, thus obtaining two frequency response curves. Equilibration of a normative QEEG database to different EEG machines is the ratio of the frequency response curves of the two amplifiers that are then used as coefficients in the power spectral analysis. This was an important step because suddenly absolute power Z-scores and normative database comparisons became possible.

The frequencies in absolute power are independent of each other, and are not distorted. It is always best to use absolute values whenever possible and not relative values, or even ratios. A ratio can change due to the denominator, or the numerator, and one cannot determine which has changed without evaluating the absolute values used to compute the ratios.

A simple method to exactly match the frequency characteristics of different amplifiers, by amplifier equilibration, is to calibrate the amplifiers using microvolt sine waves at discrete frequencies from 1–40 Hz, and inject the sine waves into the inputs of the EEG amplifiers (see Fig. 5.4). Then take the ratio of the microvolt values at each frequency, and use the ratios to exactly equate the spectral output values at different frequencies for different amplifiers. This method creates a universal equilibration process so that microvolts in a given amplifier are equal to microvolts in all other amplifiers, including the normative database amplifiers. By equilibrating amplifiers, direct comparisons between a given patient's EEG and the normative database means and standard deviations are valid and meaningful.

B. General method to produce a valid instantaneous Z-score EEG database

Figure 5.5 illustrates a step-by-step procedure by which the Z-instantaneous-score normative EEG database was validated, and sensitivities calculated. The left side of the figure is the edited, artifact clean, and reliable digital EEG time series, which may be re-referenced or re-montaged, and is then analyzed in either the time domain or the frequency domain.

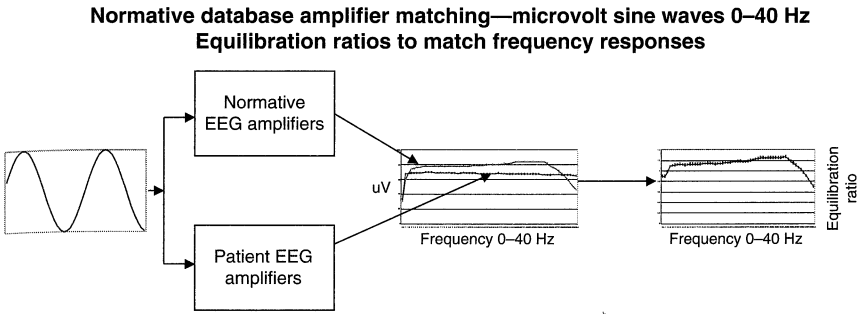


FIGURE 5.4 Flow chart of the amplifier standardization procedure. Microvolt sine waves are injected into the input of amplifiers, and the frequency responses are calculated. The frequency response of the normative database amplifiers and the frequency response of other EEG amplifier systems are then equated, and the spectral analysis is adjusted so that there is a standardized import and matching of amplifier systems with the common unit being microvolts (uV). (Adapted from Thatcher and Lubar, 2008, in press.)

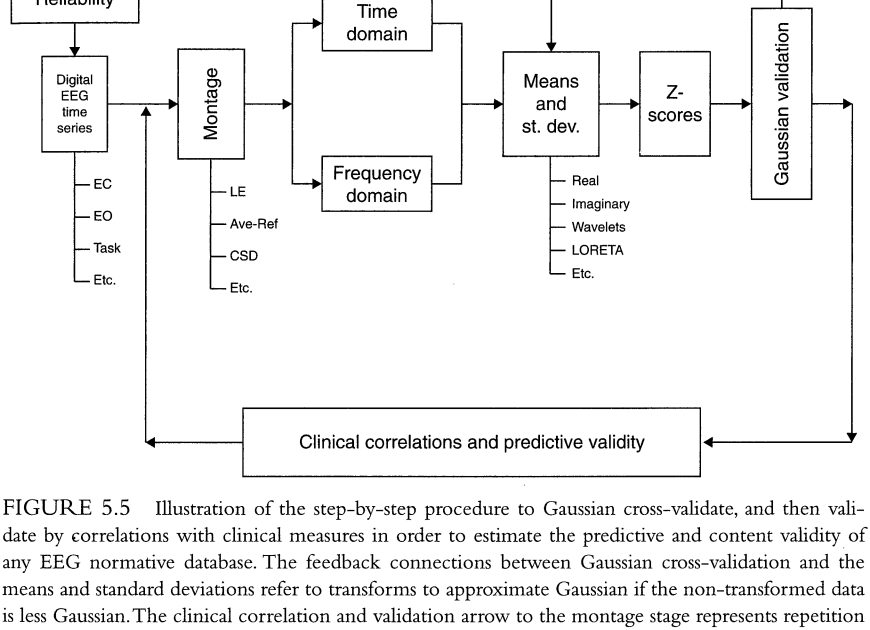


FIGURE 5.5 Illustration of the step-by-step procedure to Gaussian cross-validate, and then validate by correlations with clinical measures in order to estimate the predictive and content validity of any EEG normative database. The feedback connections between Gaussian cross-validation and the means and standard deviations refer to transforms to approximate Gaussian if the non-transformed data is less Gaussian. The clinical correlation and validation arrow to the montage stage represents repetition of clinical validation to a different montage, or reference, or condition such as eyes-open, active tasks, eyes-closed, etc. to the adjustments and understanding of the experimental design(s). (From Thatcher *et al.*, 2003.)

C. Age groupings of the instantaneous Z-score normative population

The selected normal subjects are grouped by age, with sufficiently large sample size, and the means and standard deviations of the EEG time series and/or frequency domain analyses computed for each age group. Transforms are applied to approximate a Gaussian distribution of the EEG measures that comprise the means. Once approximation to Gaussian is completed, Z-scores are computed for each subject in the database, and leave one out Gaussian cross-validation was computed in order to arrive at an optimum Gaussian cross-validation sensitivity. Finally, the Gaussian validated norms are subjected to content and predictive validation procedures such as correlation with neuropsychological test scores and intelligence, etc., and also discriminant analyses, neural networks, and outcome statistics, etc.

The content validations are with respect to clinical measures such as intelligence, neuropsychological test scores, school achievement, clinical outcomes, etc. The predictive validations are with respect to the discriminative, statistical, or neural network clinical classification accuracy. Both parametric and non-parametric statistics are used to determine the content and predictive validity of a normative EEG database.

Thatcher and Lubar (2008) show the number of subjects per year in the normative EEG lifespan database. It can be seen that the largest number of subjects are in the younger ages (e.g., 1–14 years, N = 470) when the EEG is changing most rapidly. As mentioned previously, a proportionately smaller number of subjects represent the adult age range from 14–82 years (N = 155). The Z-score normative database includes a total of 625 carefully screened individual subjects ranging in age from 2 months to 82 years. In order to increase the time resolution of age, sliding averages were used for the stratification in NeuroGuide™, and for instantaneous Z-scores (Thatcher *et al.*, 2003). Two-year means were computed using a sliding average with 6-month overlap of subjects. This produced a more stable and higher age resolution normative database, and a total of 21 different age groups. For the 21 age groups, age ranges, and number of subjects per age group see Thatcher and Lubar (2008).

VII. CASE STUDY 1: JACK

In recent years, several neurofeedback approaches have been used to treat human epilepsy but only two have received extensive research and publication. The first, and original approach, as determined by Sterman and Friar (1972) enhances SMR activity while inhibiting the lower frequencies. The second, as illustrated by Kotchoubey *et al.* (2001), trains patients to control slow cortical potentials. Both techniques are effective in reducing seizure activity.

Recent advancements in the reliability of QEEG databases, most notably single-HZ bins and broadly-based coherence determinations, have led to the

development of a third approach to the normalization of EEG in patients with epilepsy. These innovations have made it possible to more precisely characterize the power and coherence abnormalities of drug-resistant epilepsy. As demonstrated by Walker (2005), the general methodology is to identify the most significant abnormalities and train those areas with neurofeedback. Abnormal magnitude (power) indices are addressed first followed by deviant coherence values. This treatment method, combined with Z-score training, eventually proved successful with a client with medication-resistant, focal epilepsy.

Jack was a three-year-old male. The client's epilepsy was expressed as atonic, absence, and myoclonic seizures. After approximately one year of symptom-based neurofeedback treatment that produced brief periods of seizure control, Jack suffered a mild concussive head injury in the right orbital region. His seizure activity increased significantly. Three to four hundred microvolt inter-ictal epileptiform discharges were observed in the raw EEG trace. His paroxysmal activity began to generalize with a multi-spike focus. These new clinical developments proved resistant to symptom-based neurofeedback training. A new treatment strategy was developed that consisted of 2-channel inhibit protocols followed by coherence training based on the abnormalities revealed in a QEEG analysis.

These protocols were focused on the slower frequencies that tend to propagate seizure activity. The inhibit training had an immediate positive effect on seizure frequency, as well as the frequency and voltage of the patient's spike and wave complexes. The patient gained seizure control during this phase of treatment. Coherence training was begun with a focus on hypo-coherence in the lower frequencies. Seizure activity reappeared during the coherence phase of training.

This pattern was repeated during a subsequent trial of inhibit- and coherence-based training. The client gained seizure control during the inhibit phase of training only to relinquish it while undergoing coherence work. It appeared that the patient was responding negatively to traditional coherence training as evidenced by the second QEEG (Fig. 5.7). A slight variant in this round—the paroxysmal activity reappeared during the end of power training—suggested power training alone was not enough. Since standard coherence training seemed to make the patient worse, another form of coherence training was needed.

Traditional coherence training attempts to move coherence in a linear fashion from greater to lesser, or vice versa. Coherence is rewarded only when it moves in one direction. Z-score range training reinforces coherence when it remains inside a range of positive and negative Z-scores—a ceiling and a floor. Coherence is allowed to fluctuate between hyper-coherence and hypo-coherence. Z-score training exercises coherence within a range that can be altered as the trainee improves performance. The band of Z-scores trained can be narrowed, shaping the coherence toward less deviance.

This form of coherence training may be superior to traditional methods. Initial clinical results suggest that unlike conventional coherence approaches, Z-score coherence range training is less likely to produce the iatrogenic effects common to

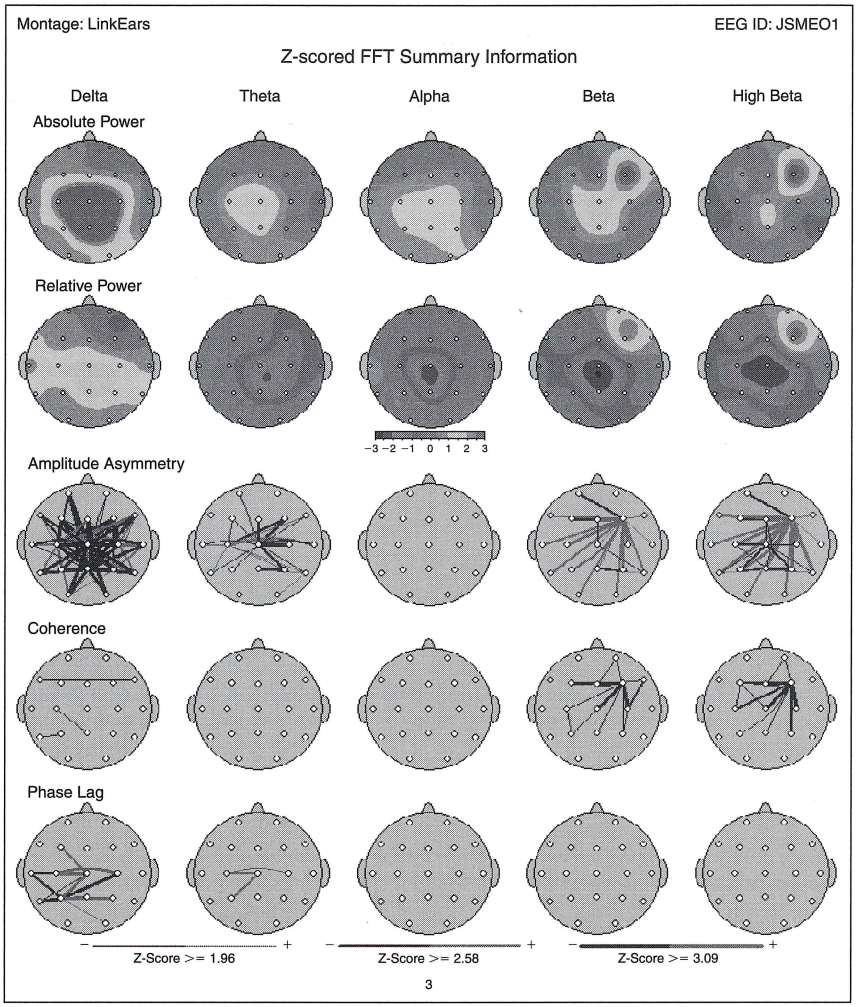


FIGURE 5.6 Jack's first QEEG revealing abnormal slow wave activity in central and parietal regions combined with delta and beta coherence abnormalities (see color plate).

overtraining. Two rounds of standard coherence training had not produced positive clinical results with Jack. After several weeks of Z-score coherence range training, he gained lasting seizure control. The post-treatment brain maps reveal a largely resolved set of coherence values (Fig. 5.8). As of the time of writing, the patient has maintained seizure control with a brief lapse for over one and one half years.

That lapse occurred when the patient was removed from medication, and a 24-hour video EEG was performed in an attempt to eliminate medication. In addition to the seizure activity, the test revealed continuous spike and wave

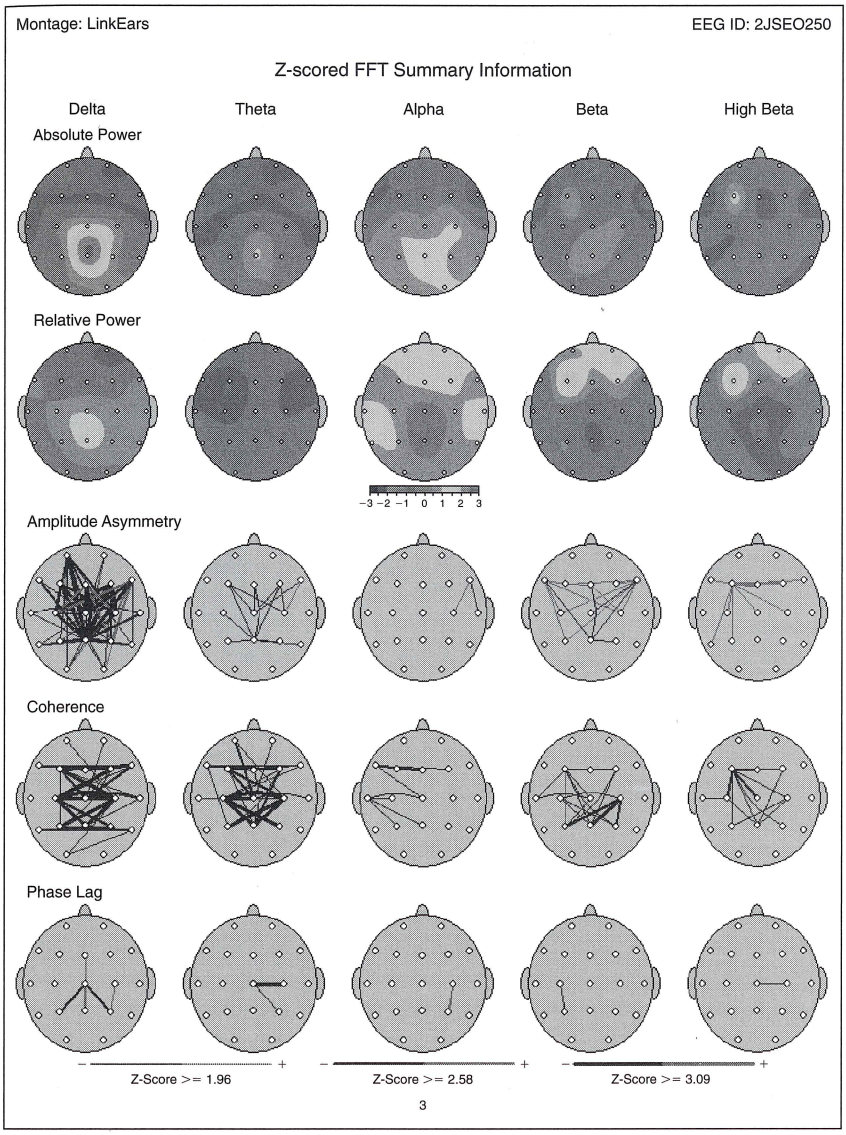


FIGURE 5.7 Significant increase in hypo-coherence in all bands after traditional coherence training (see color plate).

complexes during slow wave sleep. This prompted the review of a previous overnight EEG which had determined that, at that time, the patient had reached the diagnostic criteria for electrical status epilepticus during slow wave sleep (ESES). ESES is a rare disorder that causes neuropsyhological impairment in almost all cases according to Tassinari and colleagues (Tassinari et al., 2000). Despite a positive

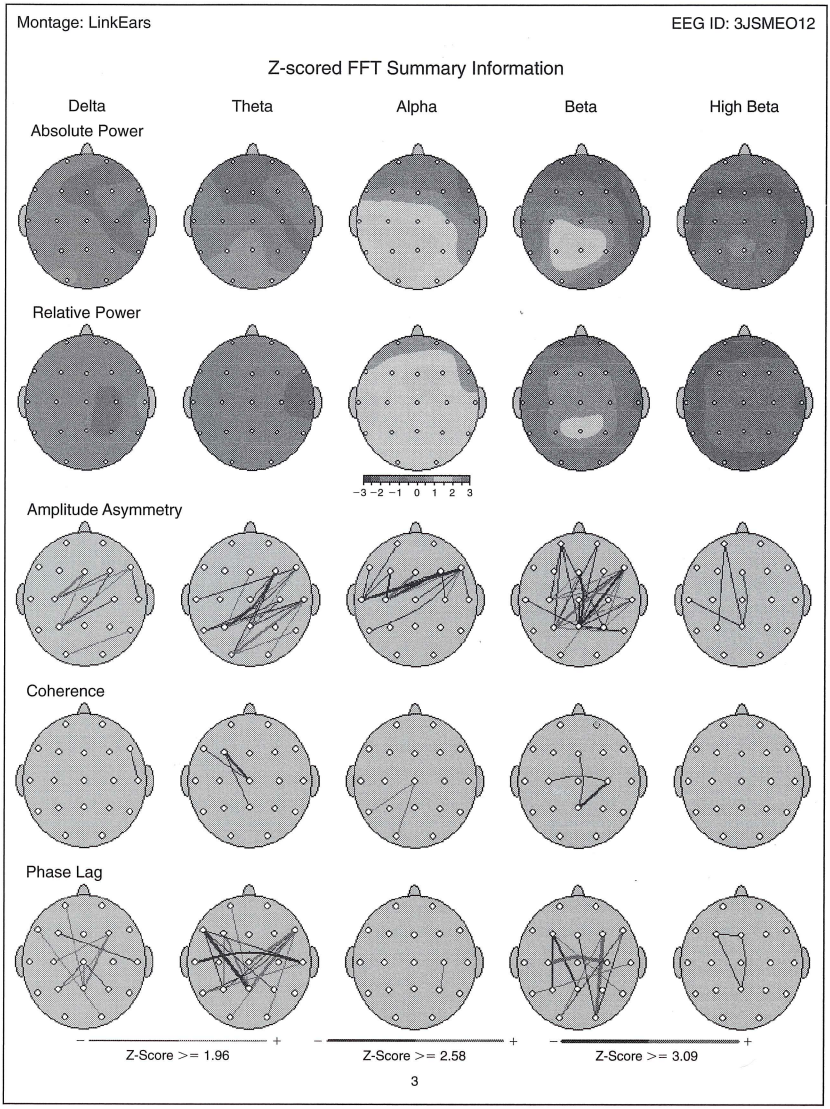


FIGURE 5.8 Substantial remediation of abnormal coherence values after Z-score coherence range training (see color plate).

seizure prognosis, ESES leaves 50% of children diagnosed with the syndrome with profound cognitive deficits (Tassinari and Galanopoulou, 1992, 2000). The most recent overnight EEG revealed a significant reduction in the frequency and magnitude of inter-ictal epileptiform discharges. While he no longer

met the criteria for ESES, the continued presence of spike and wave activity created a significant vulnerability to the development of cognitive dysfunction. Additionally, Jack could not be without medication for his seizure disorder. For those reasons, it was determined that another round of neurofeedback was indicated.

The client sat for an additional course of 2-channel inhibit and coherence training. This time Z-score monitoring and training were employed from the beginning of treatment with two positive clinical effects. Because of the software's ability to reveal instantaneous coherence and magnitude values compared to Neuroguide's normative database, it was possible to alter clinical decisions that were initially based on the QEEG. Three coherence and four magnitude protocols were indicated by the QEEG. Traditionally, these protocols would be trained approximately five times each, totaling 35 sessions. The observation of absolute power values during inhibit training indicated resolution of those deviances in less than five sessions at several locations. Moreover, the Z-score software suggested far less deviance in slow wave activity at two locations than did the QEEG. After repeated monitoring of those sites, demonstrating flexibility within normal limits, they were eliminated from the training regimen.

At the end of power training, a Z-score assessment of coherence revealed significant differences from the results of the QEEG suggesting that the resolution of magnitude impacted coherence in a normative direction. Four 2-channel coherence Z-score range training sessions at three locations comprised the connectivity protocols in this round of treatment. At 20 total sessions, this treatment course was approximately one-third to one half the number of a traditional neurofeedback treatment course of 30–40 sessions. In this case the shortened treatment is the direct result of the combination of symptom resolution and the observation of less deviant magnitude and coherence values made possible by real-time Z-score monitoring.

The client has been seizure-free for one year since his brief lapse. He is currently prescribed a small fraction of his anticonvulsive medication with possible elimination in the near future. The patient tested into a gifted and talented program, and is thriving in the first grade with no indication of cognitive deficit.

VIII. CASE STUDY 2: JOHN

John, a seventy-three-year-old Caucasian male, presented in treatment after suffering a brain tumor. A pre-treatment biopsy of the tumor caused hemorrhaging in the left temporal lobe just below T5. He submitted to several rounds of chemotherapy resulting in the complete elimination of all evidence of the cancer. At presentation the client could not read or drive due to right vision field neglect. He struggled to use the telephone, listen to the radio, watch television, or make sense

of conversation. The patient suffered with Acoustico-agnostic Aphasia, an inability to recognize phenomes (Luria 1973). In addition, expressive speech was severely compromised. He had difficulty with articulation and word finding. He struggled to sustain attention and concentration. Moreover, the client had memory deficits such that he would forget the activity he was engaged in while performing it, and would often have trouble recalling the simplest instructions immediately after they had been given. He was frequently in a state of confusion and befuddlement.

The client's QEEG revealed increases in absolute and relative power of delta and theta in the area of his hemorrhage, and diffuse increases of absolute power of 6 and 7 Hz (Fig. 5.9). There were decreases in coherences of delta and theta—some greater than five standard deviations— involving the entire left hemisphere. The client completed approximately 66 sessions of traditional 2-channel inhibit and coherence training. All his symptoms improved. He was better able to drive, talk on the telephone, read, and watch television. There were several deficits that had not completely resolved. He experienced words "jumping around" on the page while he read. He was unhappy with his processing speed. Accustomed to reading several papers per day, he now struggled to read one. The patient continued to exhibit right vision field neglect. He often labored with word finding difficulty.

The client submitted to another QEEG. It revealed little change in left hemisphere coherence and power values from the first QEEG (Fig. 5.10). The left hemisphere remained almost completely disconnected from the right. However, the second QEEG discovered increased hyper-coherence in delta, theta and high beta in the right, undamaged hemisphere. Several studies suggest this shift as a possible compensatory mechanism in patients with traumatic brain injury (Just and Thornton, 2007, 2005). The Z-score software confirmed the findings of the second QEEG. Two-channel inhibit training based on a reading difference map was employed in the occipital and temporal lobes to immediate positive effect. The magnitude deviations were substantially improved with a rapid remediation in symptoms. The client reported that the words on the page no longer moved and he was reading more efficiently.

Right vision field neglect was still evident. Despite significant improvement in reading, the client reported that he often "missed" the last several words of a sentence. The patient reported that the right rear tail light of the car traveling in front of him was not perceptible. A four-channel Z-score protocol targeting 23 training parameters was employed. Included in that protocol were delta and theta absolute power, and delta, theta, and beta coherence. Simultaneously, 6–7 Hz was inhibited in all four channels. Visual, memory, and association areas were targeted. This protocol was based on a combination of the results of the QEEG and visual inspection of the real-time Z-score values (Fig. 5.11).

After three sessions, the trained Z-scores showed remarkable movement toward normative values. Absolute power and coherence indices improved, in some cases demonstrating flexibility of almost two standard deviations. All Z-scores revealed a shift toward more plasticity and less deviance (Fig. 5.12). The patient reported

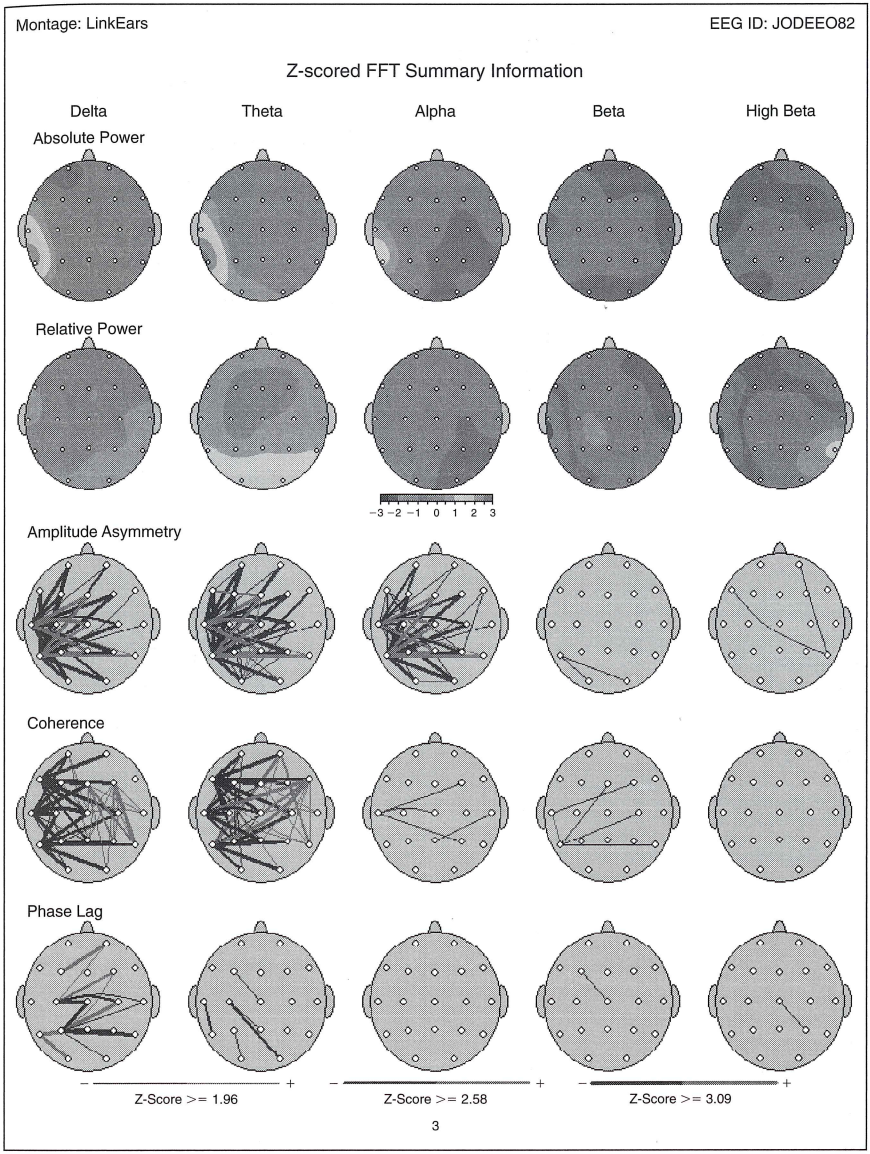


FIGURE 5.9 John's first QEEG demonstrating focal slow wave activity over the area of the hemorrhage, and theta abnormalities in occipital, parietal and temporal lobes with left hemisphere hypo-coherence and right hemisphere hyper-coherence (see color plate).

that his right vision field neglect was greatly improved. He was consistently able to read the last several words of each sentence. He reliably observed the right rear tail light of cars preceding him. Several sessions later, he stated that he was able to perceive the cars stopped at intersections on his right.

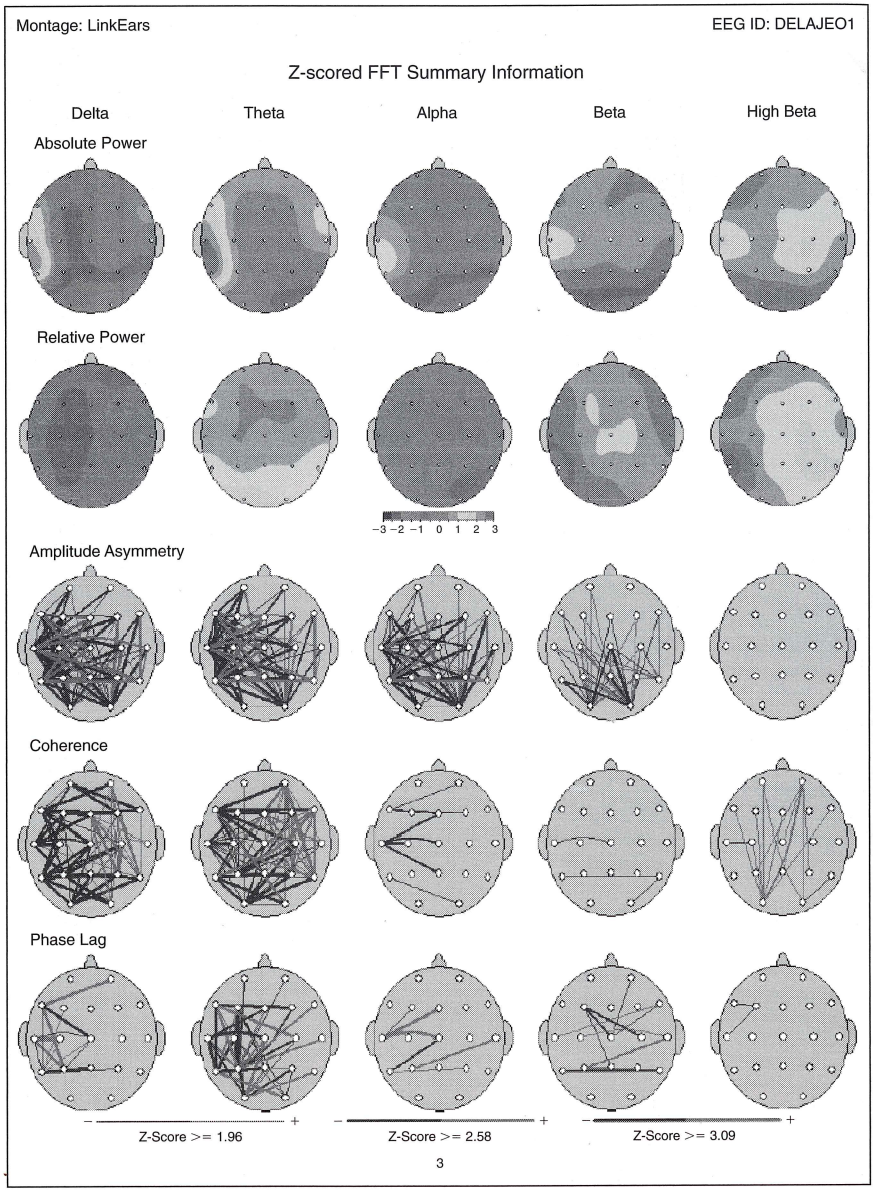


FIGURE 5.10 After 60 sessions of traditional inhibit and coherence training. Note the significant increase in hyper-coherence in the right hemisphere (see color plate).

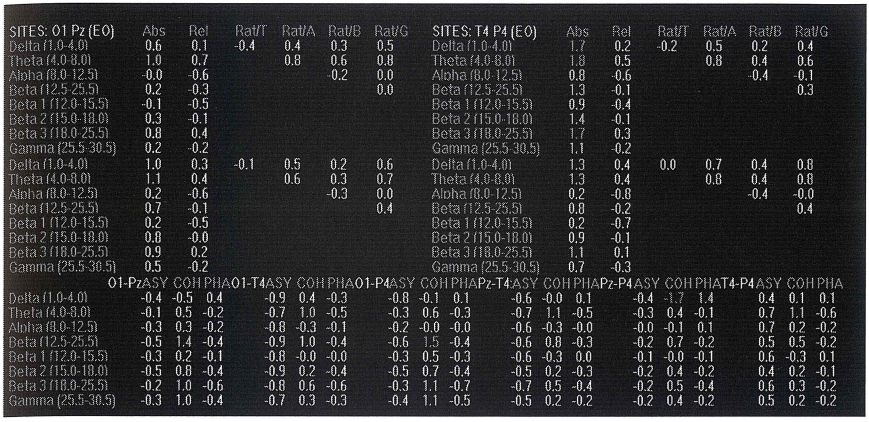


FIGURE 5.11 Four-channel Z-score protocol based on the QEEG and this Z-score assessment (see color plate).

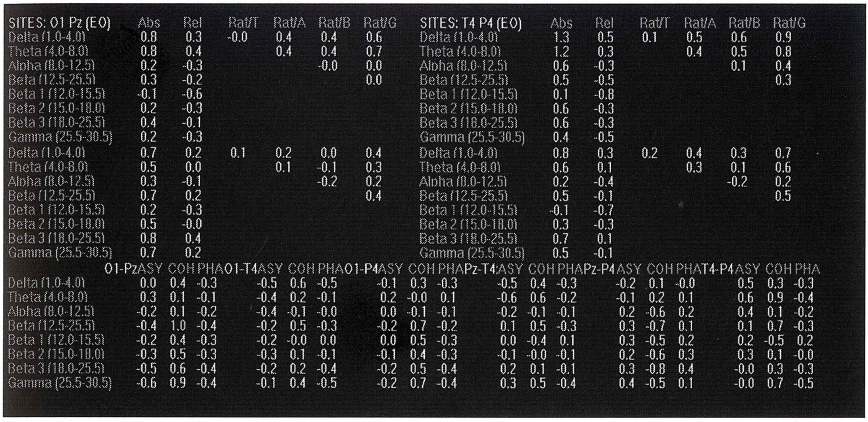
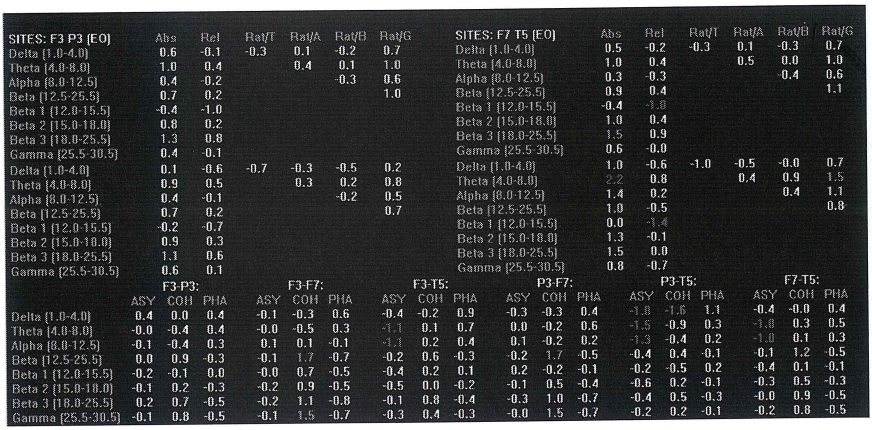


FIGURE 5.12 After three sessions of training, Z-scores reveal substantial remediation (see color plate).

Birnbaumer (2007) has suggested that if the neuronal assemblies adjacent to the injury, rather than the homolog in the contra-lateral hemisphere, assume the function of damaged neurons more recovery is possible. Incorporating this strategy to address the client's expressive speech difficulties, a protocol targeting the left hemisphere was developed.

In addition to the damaged area of the surpramarginal gyrus, Broca's area, the ventral frontal and posterior parietal lobes were trained (Illustration 10). Twenty-six training parameters including delta and theta absolute power and coherences of delta, beta and gamma were employed. After 11 sessions of Z-score training the measures had improved substantially. Coherence values were demonstrably more flexible, frequently moving within one standard deviation. Absolute power indices



SITES: F3 P3 [EO]	Abs	Rel	Rat/T	Rat/A	Rat/B	Rat/G
Delta [1.0-4.0]	0.6	-0.1	-0.3	0.1	-0.2	0.7
Theta [4.0-8.0]	1.0	0.4		0.4	0.1	1.0
Alpha [8.0-12.5]	0.4	-0.2			-0.3	0.6
Beta [12.5-25.5]	0.7	0.2				1.0
Beta 1 [12.0-15.5]	-0.4	-1.0				
Beta 2 [15.0-18.0]	0.8	0.2				
Beta 3 [18.0-25.5]	1.3	0.8				
Gamma [25.5-30.5]	0.4	-0.1				
Delta [1.0-4.0]	0.1	-0.6	-0.7	-0.3	-0.5	0.2
Theta [4.0-8.0]	0.9	0.5		0.3	0.2	0.8
Alpha [8.0-12.5]	0.4	-0.1			-0.2	0.5
Beta [12.5-25.5]	0.7	0.2				0.7
Beta 1 [12.0-15.5]	-0.2	-0.7				
Beta 2 [15.0-18.0]	0.9	0.3				
Beta 3 [18.0-25.5]	1.1	0.6				
Gamma [25.5-30.5]	0.6	0.1				

SITES: F7 T5 [EO]	Abs	Rel	Rat/T	Rat/A	Rat/B	Rat/G
Delta [1.0-4.0]	0.5	-0.2	-0.3	0.1	-0.3	0.7
Theta [4.0-8.0]	1.0	0.4		0.5	0.0	1.0
Alpha [8.0-12.5]	0.3	-0.3			-0.4	0.6
Beta [12.5-25.5]	0.9	0.4				1.1
Beta 1 [12.0-15.5]	-0.4	-1.0				
Beta 2 [15.0-18.0]	1.0	0.4				
Beta 3 [18.0-25.5]	1.5	0.9				
Gamma [25.5-30.5]	0.6	-0.0				
Delta [1.0-4.0]	1.0	-0.6	-1.0	-0.5	-0.0	0.7
Theta [4.0-8.0]	2.2	0.8		0.4	0.9	1.5
Alpha [8.0-12.5]	1.4	0.2			0.4	1.1
Beta [12.5-25.5]	1.0	-0.5				0.8
Beta 1 [12.0-15.5]	0.0	-1.4				
Beta 2 [15.0-18.0]	1.3	-0.1				
Beta 3 [18.0-25.5]	1.5	0.0				
Gamma [25.5-30.5]	0.8	-0.7				

	F3-P3:			F3-F7:			F3-T5:			P3-F7:			P3-T5:			F7-T5:		
	ASY	COH	PHA	ASY	COH	PHA	ASY	COH	PHA	ASY	COH	PHA	ASY	COH	PHA	ASY	COH	PHA
Delta [1.0-4.0]	0.4	0.0	0.4	-0.1	-0.3	0.6	-0.4	-0.2	0.9	-0.3	-0.3	0.4	-1.8	-1.6	1.1	-0.4	-0.0	0.4
Theta [4.0-8.0]	-0.0	-0.4	0.4	-0.0	-0.5	0.3	-1.1	0.1	0.7	0.0	-0.2	0.6	-1.5	-0.9	0.3	-1.8	0.3	0.5
Alpha [8.0-12.5]	-0.1	-0.4	0.3	0.1	0.1	-0.1	-1.1	0.2	0.4	0.1	-0.2	0.2	-1.3	-0.4	0.2	-1.0	0.1	0.3
Beta [12.5-25.5]	0.0	0.9	-0.3	-0.1	1.7	-0.7	-0.2	0.6	-0.3	-0.2	1.7	-0.5	-0.4	0.4	-0.1	-0.1	1.2	-0.5
Beta 1 [12.0-15.5]	-0.2	-0.1	0.0	-0.0	0.7	-0.5	-0.4	0.2	0.1	0.2	-0.2	-0.1	-0.2	-0.5	0.2	-0.4	0.1	-0.1
Beta 2 [15.0-18.0]	-0.1	0.2	-0.3	-0.2	0.9	-0.5	-0.5	0.0	-0.2	-0.1	0.5	-0.4	-0.6	0.2	-0.1	-0.3	0.5	-0.3
Beta 3 [18.0-25.5]	0.2	0.7	-0.5	-0.2	1.1	-0.8	-0.1	0.8	-0.4	-0.3	1.0	-0.7	-0.4	0.5	-0.3	-0.0	0.9	-0.5
Gamma [25.5-30.5]	-0.1	0.8	-0.5	-0.1	1.5	-0.7	-0.3	0.4	-0.3	-0.0	1.5	-0.7	-0.2	0.2	-0.1	-0.2	0.8	-0.5

FIGURE 5.13 First Z-score training of F3/P3/F7/T5. Note the damage in the temporal area at T5 reflected in abnormal absolute power Z-scores, and the significant deviation in connectivity measures (see color plate).

including the damaged area of the temporal lobe that had resisted traditional training, demonstrated similar remediation (Fig. 5.13). More importantly, the client was able to express himself with much more precision. More often appropriate and precise nouns such as "barn" took the place of the more general "animal house." Overall, the improvement in the production of coherence in conversation was marked, and confirmed by report of family and friends.

IX. CASE STUDY 3: SL

This section will describe the experience of two of the chapter authors, Lambos and Stark, with Z-score training in SL, a seven-year-old right-handed male who was brought to us by his parents for help with discipline problems, both at home and in the classroom, and a possible diagnosis of ADHD. As per our usual procedures, we carefully interviewed the child and his parents, and conducted appropriate neuropsychological testing as well as a 19-channel QEEG.

S's history includes a normal vaginal delivery following an unremarkable gestation. He developed normally, and met developmental milestones within normal time periods. He was breast-fed, and has had few infectious disease problems. No head trauma, encephalitis or other common causes of insult to the brain were reported. With respect to his school experience, S has been a rapid learner but his teachers noted a tendency to become easily excited and aggressive with other children. Some teachers and professionals felt he could be classified as ADHD. The interview revealed that his home environment was somewhat chaotic. S is the oldest of four children age 2 to 7, all of whom we would describe as highly active. During his interview, S approached levels of activity that could be

classified as hyperactive. His mother reported that she is constantly dividing her attention among the children and S's due to his hyperactive behavior.

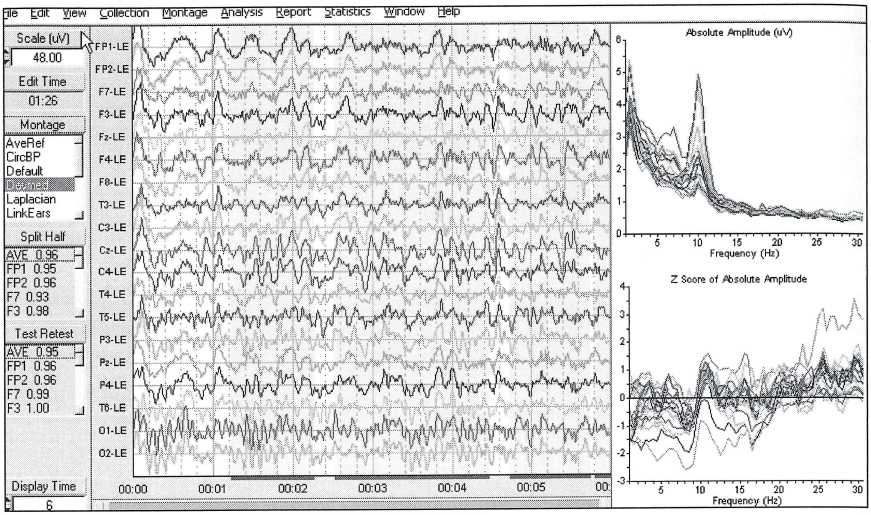
We collected neuropsychological data from the Conner's parent and teacher rating scales, and administered the Connors CPT-II, and the NEPSY neuropsychological battery for children. His results on the neuropsychological tests showed both strengths and weaknesses in the standard scores, but none of the NEPSY domains were statistically significant. Both the Connor's scales and the CPT-II showed a mixture of normal responding, inattention and impulsivity. The only statistically significant measure on the CPT-II was perseverations. The test reported an equal probability of his belonging to the ADHD and non-clinical populations. Observation of his behavior during testing showed the majority of his difficulties were associated with excess activity rather than an inability to attend.

After analyzing his QEEG results (see below), we decided to train S with targeted EEG-biofeedback using the BrainMaster Z-score normalization protocol over four channels using the "Percent Z-OK" protocol. The threshold for percent Z in target was initially set at 85%, and the range of Z-scores was initially set at +/− 2.0. Sensors were placed at sites F3-F4/P3-P4 as per the QEEG results. Following 21 sessions of Z-score training with these parameters, we conducted a second QEEG, which is shown below compared to the pre-training results (QEEG #1). The results are described below for the eyes-closed and eyes-open recording conditions, respectively.

A. Eyes-closed condition

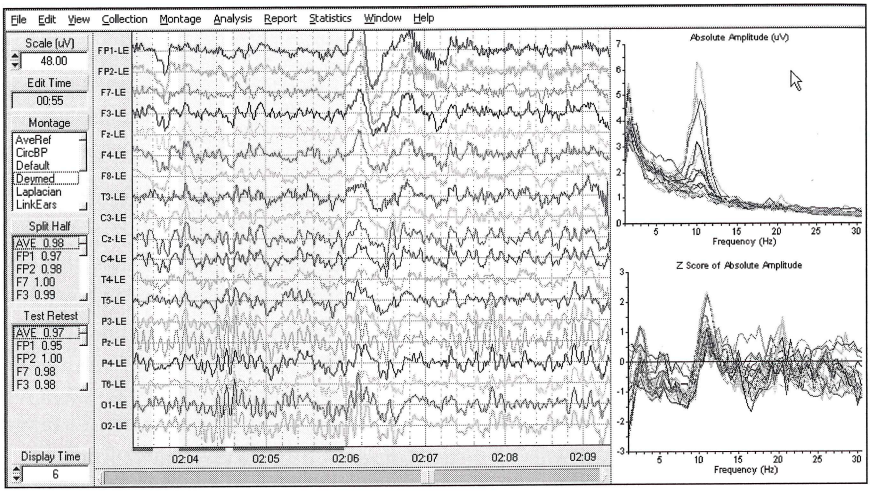
Raw tracings, amplitude frequency distributions and Z-score frequency distributions: See Figs 5.14A and 5.14B. Even in the raw wave and amplitude by frequency graphs, normalization of S's EEG pattern is obvious. The large aberrant wave forms seen in frontal sites (presumably caused by motor activity) during Q1 decreased significantly, and the overall distribution approached normality. More importantly, his Z-score distribution in the eyes-closed state following training was entirely within +/− 1.5 standard deviations of the reference population mean with the single exception of his dominant frequency, which we deemed not to be of clinical concern. S's brain function in the eyes-closed state has normalized as a result of EEG biofeedback.

Z-scored summary information (brain maps): See Figs 5.15A and 5.15B. The change in S's brain function is most apparent in the Z-scored summary maps. All of the measures with the exception of phase lag completely normalized in every frequency band except for the low 1–4 Hz delta range, and these significantly improved. Some coherence and amplitude asymmetry in the delta range remained, but these are difficult to interpret, and we view these as having less diagnostic relevance than the other bands (columns). The single area that remained in need of complete normalization was phase. Overall, the reduction in neural disregulation is exceptional. We have rarely seen improvements of this magnitude over the course of 20 sessions.



(A)

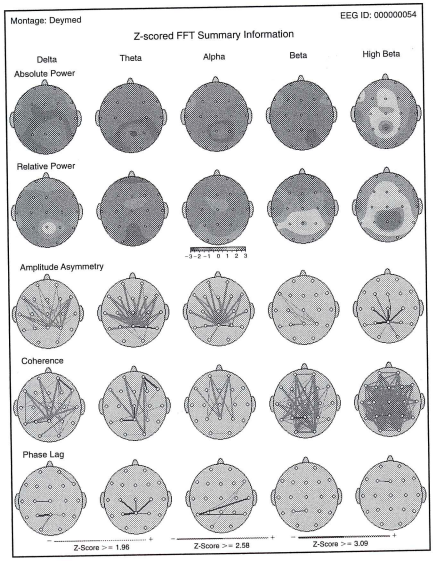
FIGURE 5.14A Q1, FFT frequency distribution, eyes-closed (see color plate).



(B)

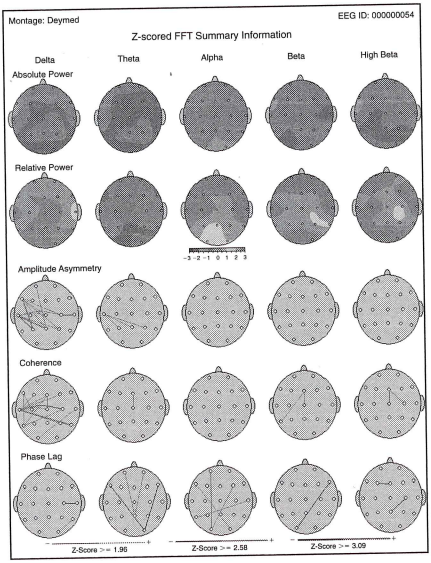
FIGURE 5.14B Q2, FFT frequency distribution, eyes-closed (see color plate).

Source localization (LORETA): See Figs 5.16A and 5.16B (Pascqual Marqui *et al.*, 1994; Pascual-Marqui, 1999). These maps show a marked reduction in localized aberrations and network communication measures consistent with the previous maps. Visually, the changes are just as striking. The extreme disregulations in parietal lobe areas, which include the pre-motor cortex, have completely normalized. The



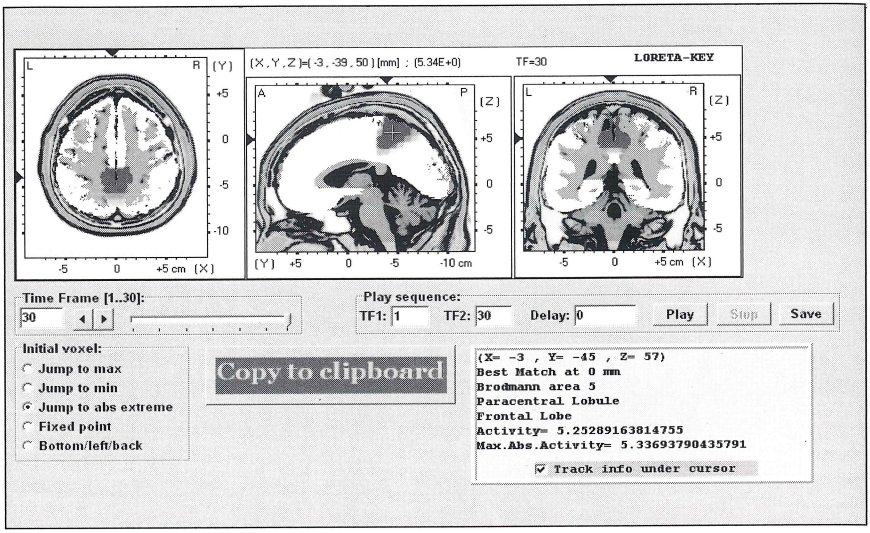
(A)

FIGURE 5.15A Q1, FFT summary EC (see color plate).



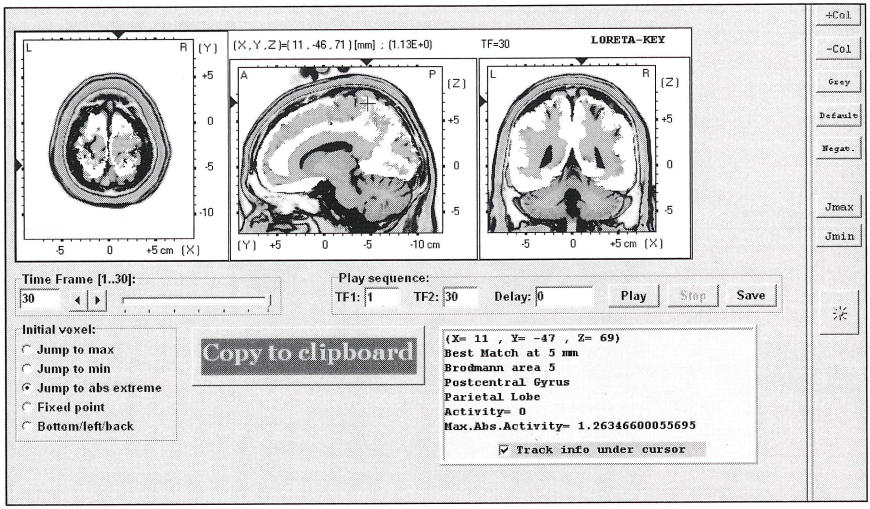
(B)

FIGURE 5.15B Q2, FFT summary EC (see color plate).



(A)

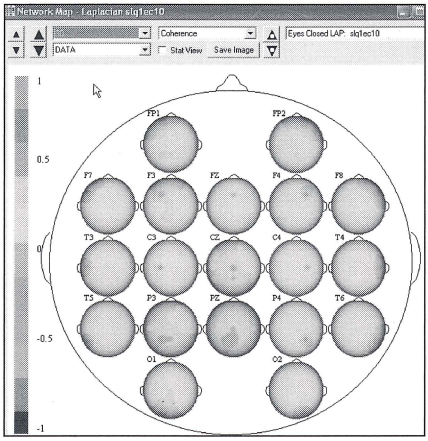
FIGURE 5.16A Q1, LORETA @ 30 EC (see color plate).



(B)

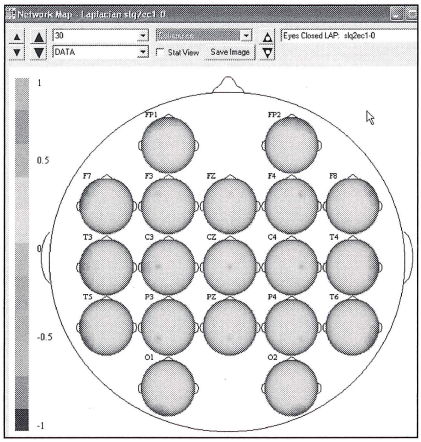
FIGURE 5.16B Q2, LORETA @ 30 Hz EC (see color plate).

dorsolateral cortex is closely associated with executive function and response inhibition, and this finding predicts significant increases in S's ability to control disruptive behaviors. SKIL network maps also show significant improvements in coherence and co-modulation at all areas. Phase measures showed more modest improvement or less reduction of significant deviations than did power, coherence or co-modulation.



(A)

FIGURE 5.17A Q1, coherence @ 30 EC (see color plate).



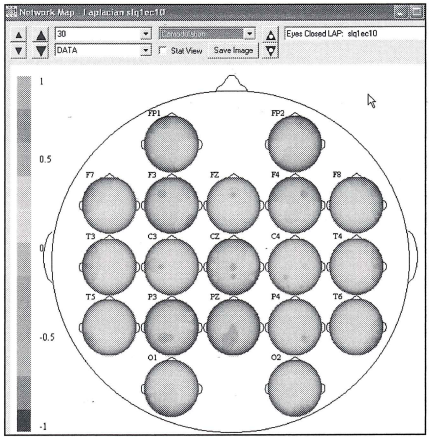
(B)

FIGURE 5.17B Q2, coherence @ 30 EC (see color plate).

The conclusion for the eyes-closed analysis is that S's pattern of neural disregulation has improved dramatically. Clinical improvements are expected to correspond to the improvement in brain functioning.

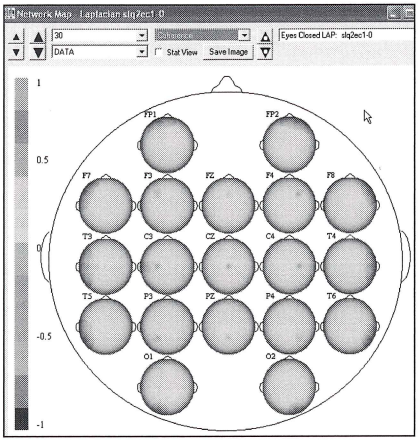
B. Eyes-open condition

Raw Tracings, Amplitude Frequency Distributions and Z-Score Frequency Distributions: See Figs 5.19A and 5.19B. Similar to the eyes-closed condition, normalization



(A)

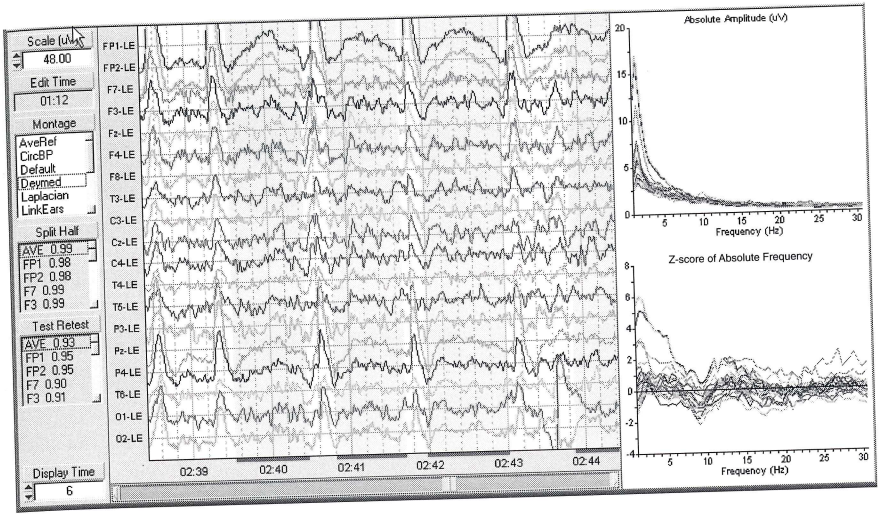
FIGURE 5.18A Q1, comod @ 30 EC (see color plate).



(B)

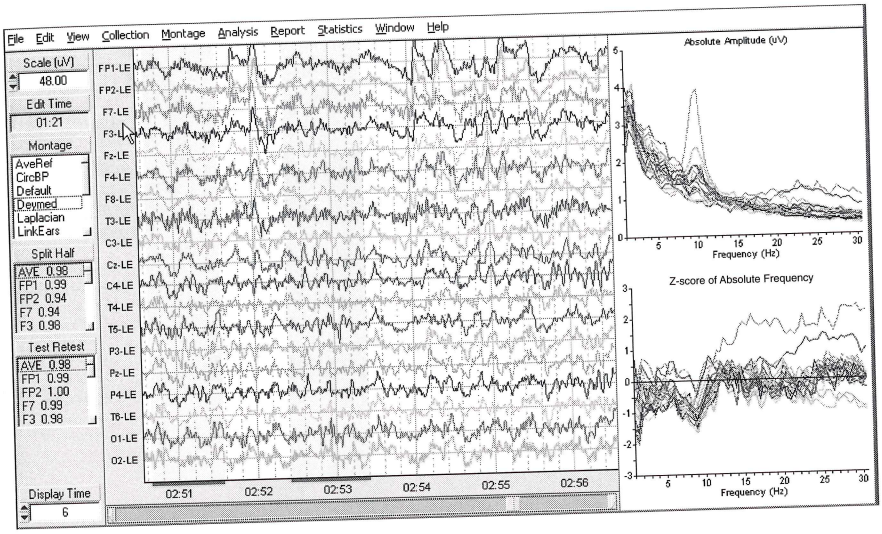
FIGURE 5.18B Q2, comod @ 30 EC (see color plate).

of S's raw wave EEG pattern is obvious. Motor ticks causing large aberrant wave forms seen in frontal sites during Q1 have decrease in both frequency and amplitude, and the overall distribution is again approaching normality. Although at first glance the high Z-scores in the 23–30 Hz beta range seem to have increased in magnitude, the diminution in delta amplitudes in Q2 has caused the scale of the Z-score graph to change from Q1 to Q2, and the relative scores are close. Site F7 remains significantly elevated in Q2, but this site is close to the junction of the massiter and frontalis (jaw and forehead) muscles, and appears to be



(A)

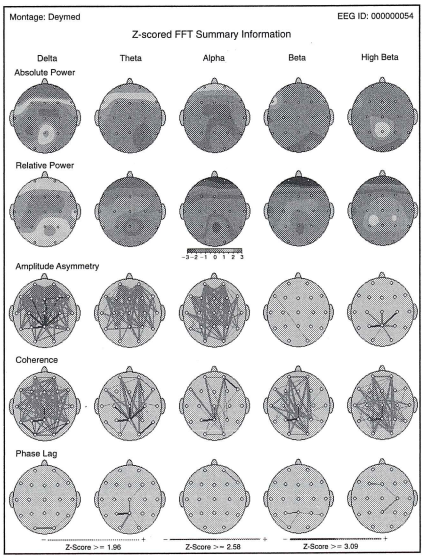
FIGURE 5.19A Q1, FFT frequency distribution, eyes-open (see color plate).



(B)

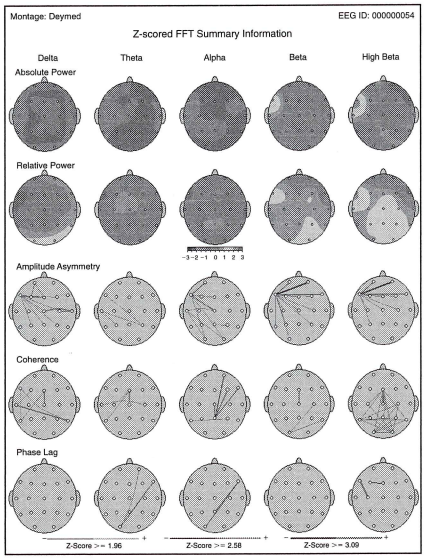
FIGURE 5.19B Q2, FFT frequency distribution, eyes-open (see color plate).

muscle artifact. This is confirmed by examination of the raw wave patterns as well as by inspection of the summary maps in Figs 5.20A and 5.20B. All other sites are within the normal range of the reference population. Similar to the eyes-closed data, S's brain function in the eyes-open state has normalized as a direct result of EEG biofeedback.



(A)

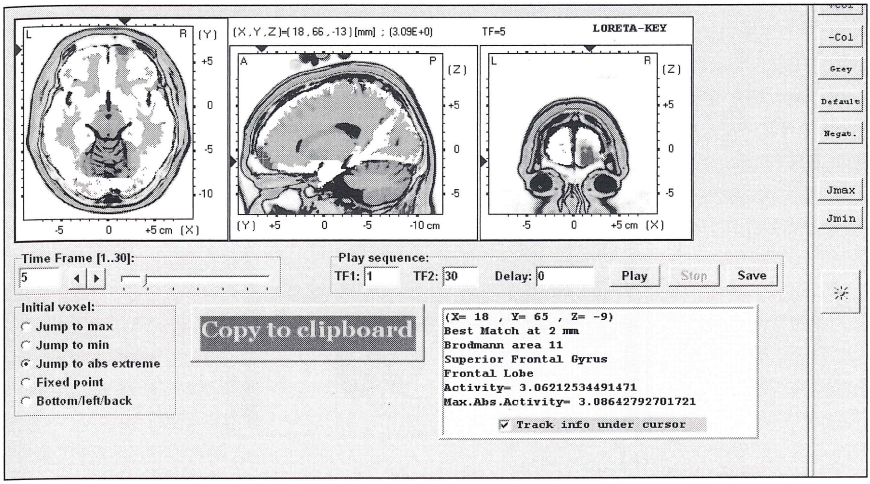
FIGURE 5.20A Q1, FFT summary EO (see color plate).



(B)

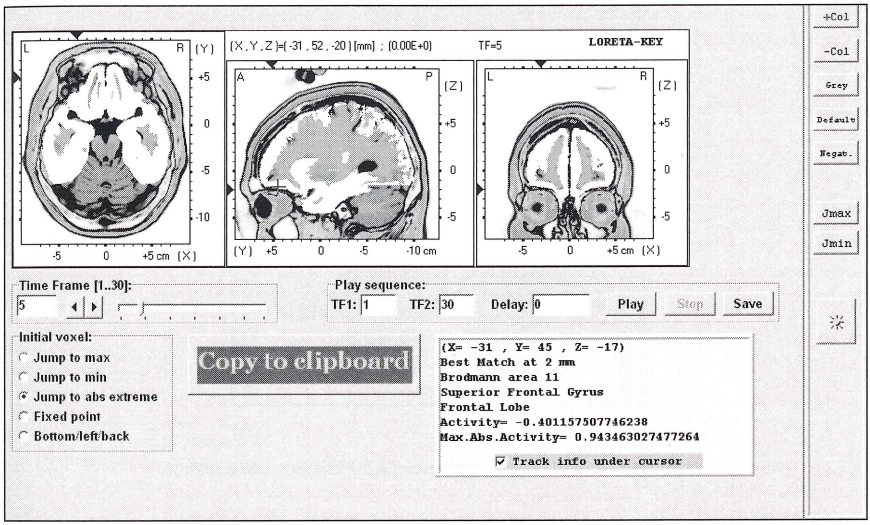
FIGURE 5.20B Q2, FFT summary EO (see color plate).

Z-scored summary information (brain maps): See Figs 5.20A and 5.20B. The change is S's brain function is also significant, although some coherence aberrations remain in the beta frequency bands. Interestingly, phase measures are improved relative to the eyes-closed condition. The low 2–4 Hz delta range measures



(A)

FIGURE 5.21A Q1, LORETA @ 5 Hz EC (see color plate).

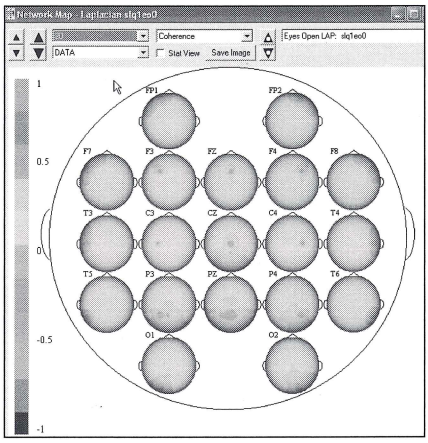


(B)

FIGURE 5.21B Q2, LORETA @ 5 Hz EC (see color plate).

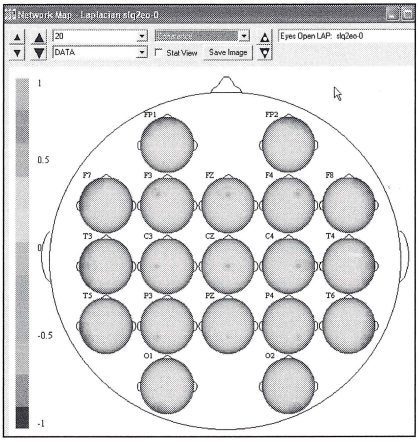
approach normalization in Q2 relative to Q1; these have significantly improved. Some coherence and amplitude asymmetry in the delta range remain, but these are difficult to interpret in any case, and have less diagnostic relevance than the other bands (columns). The reduction in neural disregulation remains striking. As with the eyes-closed condition, we are greatly encouraged by these results.

Source localization (LORETA): See Figs 5.21A and 5.21B. The LORETA analyses (Pascual Marqui *et al.*, 1994; Pascual-Marqui, 1999) once again showed



(A)

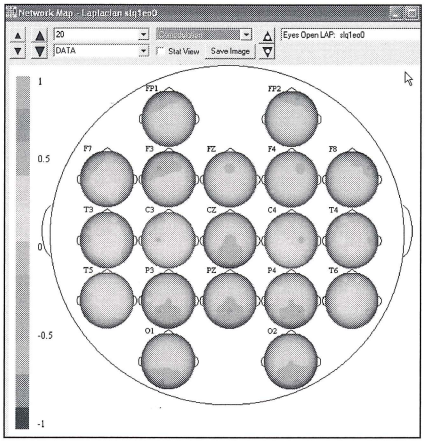
FIGURE 5.22A Q1, coherence @ 20 EO (see color plate).



(B)

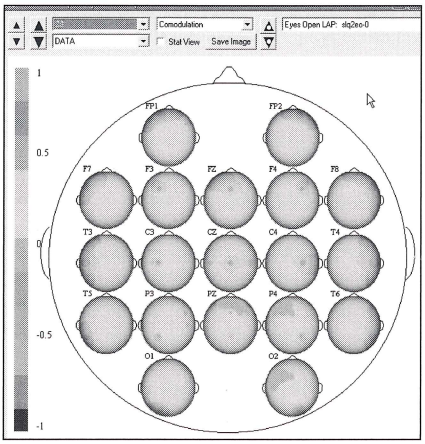
FIGURE 5.22B Q2, coherence @ 20 EO (see color plate).

a marked reduction in localized disregulation. Visually, the changes are similarly striking. SKIL network maps in DATA mode, i.e., within subject comparisons that do not use the SKIL reference database, also show significant improvements in coherence and co-modulation at all areas. Once again, phase measures show the need for continued training. The conclusion for the eyes-open analysis is thus consistent with the eyes-closed condition: S's pattern of neural disregulation has improved dramatically. Clinical improvements were noticed in training sessions and recording in session notes, and conform to markedly improved behavior reported by his teachers in school, and at home as reported by S's parents.



(A)

FIGURE 5.23A Q1, comod @ 20 EO. (see color plate)



(B)

FIGURE 5.23B Q2, comod @ 20 EO (see color plate).

X. CONCLUSIONS

Considering all of the data presented above, and the historical data at hand, 20 sessions of targeted EEG-biofeedback training using the Z-score normalization protocol resulted in significant normalization of S's neural functioning. Phase lag and related measures continue to show patterns outside the reference population norms, but all other measures normalized. His parents reported significant clinical and behavioral improvements in his presenting symptoms, which was also obvious to us in his training sessions.

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