BrainAvatar: Integrated Brain Imaging, Neurofeedback, and Reference Database System

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BrainAvatar is the next generation of BrainMaster software, supported by the Atlantis and Discovery EEG devices. It is the successor to Atlantis 3.7i, and Discovery 1.5.9, and is designated the 4.0 release. It includes all existing features and can run all existing protocols, including peripheral biofeedback, but include several innovative new capabilities, including live 3-D brain imaging for assessment and biofeedback, using the sLORETA algorithm (Pascual-Marqui, 2002).

The important new capabilities of BrainAvatar include:

- Programmable tabbed screens, 8 tabs per screen.
- Easier use of folders and settings files; ability to run from a desktop shortcut.
- Special second screen with 8 tabs for EEG review or client.
- 16 frequency bands instead of the original 8.
- New contoured and 3-D-look display panels.
- A 24-channel EEG simulator for testing, research, and sham feedback.
- Fast 2-D live topographic maps ("flat maps") (raw or z-scores).
- Fast 3-D live topographic maps on realistic head (raw or z-scores).
- Instantaneous live sLORETA projector with real-time 3-D imaging.
- Z-Builder (creates z-score templates, allows users to build reference databases).
- EEG Review and Edit screens, integrated with LLP and Z-Builder.

BrainAvatar contains all existing displays, games, etc. from our previous software. In addition, the LLP display provides a powerful, new feedback display. Rather than a graphic, sound, movie, or other display, the client watches his or her own brain activity, instantaneously. When the Region of Interest or single voxel change, the client sees it instantly, within 30 milliseconds. This provides unprecedented resolution and acuity in the feedback display. The client could see which voxels are active, their precise location, and when they activate. This provides new mind-brain connection. Similar to an fMRI in its imaging ability, this method is more than 1000 times faster. It reflects true brain electrical activity, scientifically localized in real time.

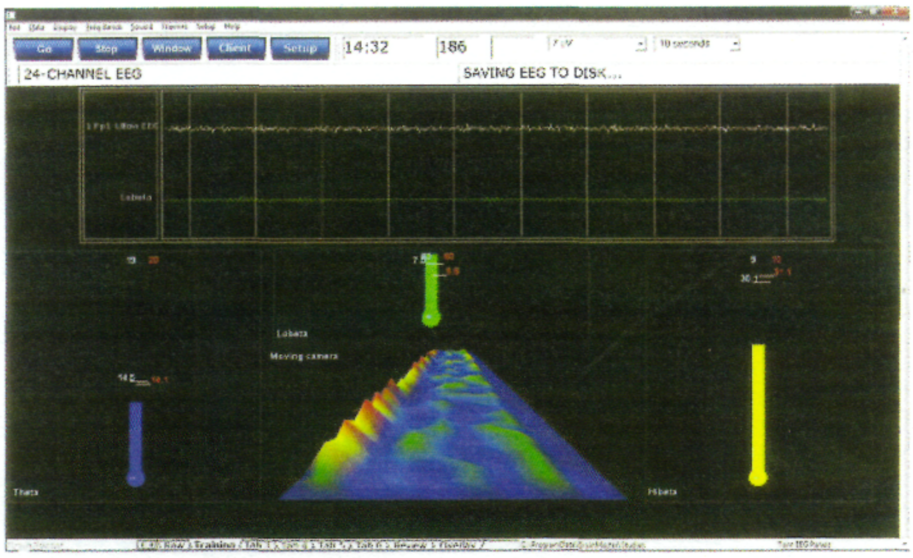

Figure 1: Flexible new screen layout tools, for up to 8 tabbed screens

These features combine to provide an unprecedented level of flexibility and ease of use. Each of the eight tabbed screens is fully programmable and can contain any displays or controls, so changing screens is now a single mouse click.

The 16 frequency bands allow the use of specific frequency ranges, and are adjustable with a resolution of 0.0001 Hz. Even slow-cortical potentials or infra-low EEG (ILF) signals can be imaged and trained. The EEG simulator is useful for testing, teaching, demonstration, and sham feedback applications. However, the most significant new features are the sLORETA-based Live LORETA Projector (LLP) and the innovative Z-Builder z-score reference creation tools.

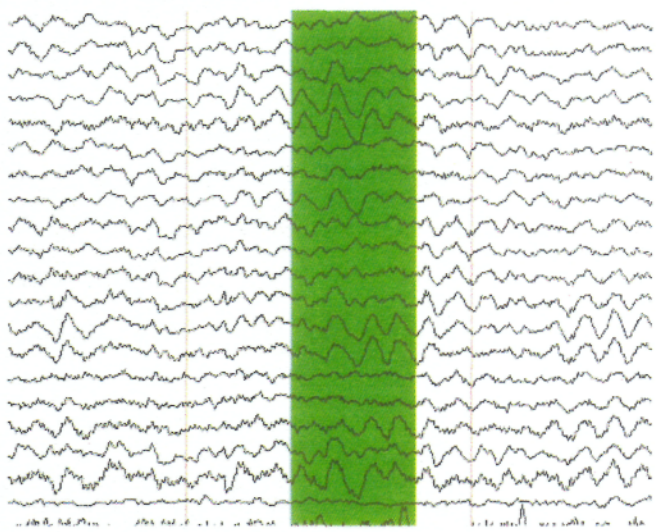

Figure 2: BrainAvatar EEG edit screens interface with the LLP projector and Z-Builder.

BrainAvatar also includes a complete set of live "flat" brain maps, as well as surface maps rendered on a 3-D head. These can be raw or z-scored maps, and can be change maps, so that a client could see what is changing in time, or what has changed since a last session.

The LLP Live LORETA Projector provides instantaneous, real-time sLORETA-based brain activity images, at a rate of 32 frames per second. This provides a brain functional imaging system that operates at brain speeds, and has high-resolution imaging capability.

BrainAvatar uses the sLORETA ("standardized LORETA") mathematics and theory, but is an entirely original implementation by BrainMaster. No software from the Key Institute is used in our system, although it is possible to use the Key Institute's LORETA and sLORETA software packages using BrainAvatar data, for research purposes. The Live Loreta Projector (LLP) provides over 30 3-D sLORETA images per second, and images can be positioned, rotated, or auto-rotated as needed for assessment or neurofeedback.

We chose to use sLORETA as the basis for BrainAvatar, rather than LORETA. Despite the fact that sLORETA requires more computations, it has higher resolution and its guaranteed zero-error localization are critical for neurofeedback applications. LORETA has a non-zero localization error, which compromises its accuracy and usefulness for neurofeedback. For any applications, particularly for live imaging and neurofeedback, sLORETA is technically superior to LORETA.

The sLORETA algorithm is based on the work of Dr. Roberto Pasqual-Marqui (2002), and has been widely validated for its accuracy. It provides a resolution of 5 mm per voxel, and has demonstrated use in a variety of studies. The most important aspect of the LLP is its speed and real-time 3-D imaging capability. The ability to visualize brain activity at the voxel-level, in real time and in multiple frequency bands, is a new capability that has not been available in any other systems. This introduces a new look and feel to neurofeedback, taking feedback from the world of simple displays, games, and videos, into witnessing one's own new brain activity.

DIFFERENCES BETWEEN LORETA AND sLORETA

The following are the major differences between LORETA and sLORETA:

- sLORETA is the successor to LORETA, introduced several years later, by Dr. Pasqual-Marqui (2002). (the yet more advanced eLORETA is now available, as well). For our purposes, sLORETA is more than sufficient, whereas LORETA would have been not quite adequate.
- sLORETA has 6,239 voxels, compared to LORETA's 2,000+ voxels.
- sLORETA uses 5-millimeter voxels, compared to LORETA's 7-millimeter voxel size.
- sLORETA does not include the amygdala, while LORETA includes the amygdala, but it is not reliable.

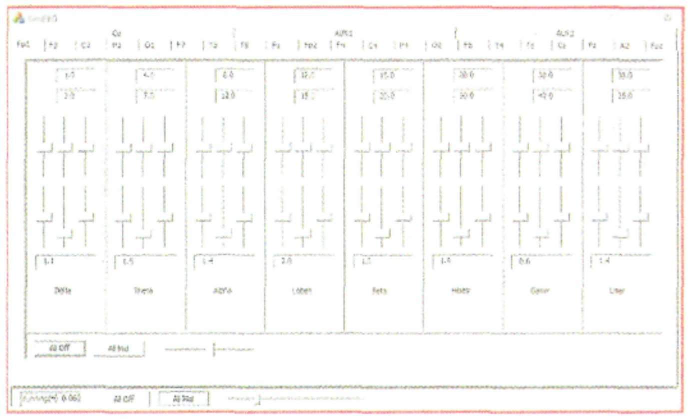

Figure 3: 24-channel EEG simulator provides a wide range of programmable test and sham signals.

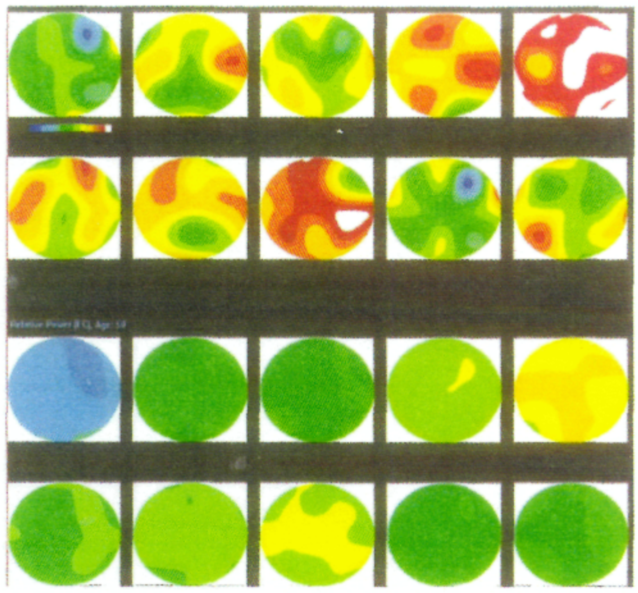

Figure 4: Real-time "Flat" maps provide instantaneous views of scalp activity as raw scores or as live z-scores.

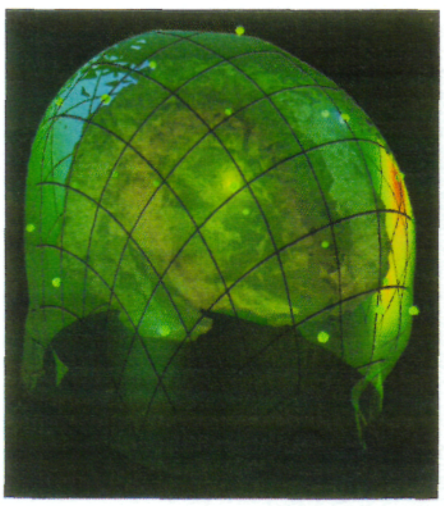

Figure 5: Simultaneous 3-D surface mapping and sLORETA projection for assessment or for biofeedback training.

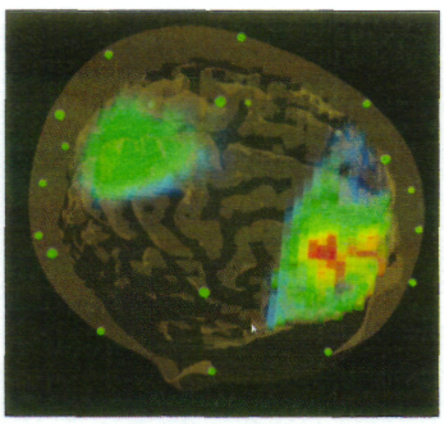

Figure 6: Instantaneous sLORETA display showing alpha band activity. The activity from the posterior cingulated gyrus is visible, as well as that from the dorsolateral frontal lobes.

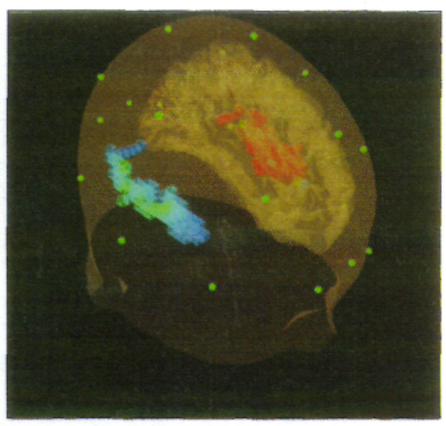

Figure 7: Live sLORETA image of the activity in the superior temporal lobes, rendered for left and right hemispheres.

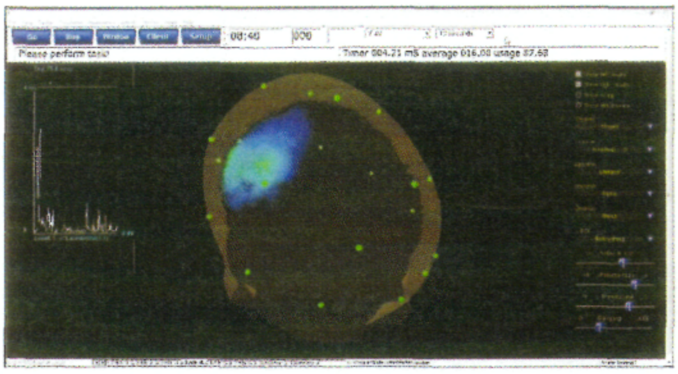

Figure 8: Example of sLORETA ROI training of occipital alpha

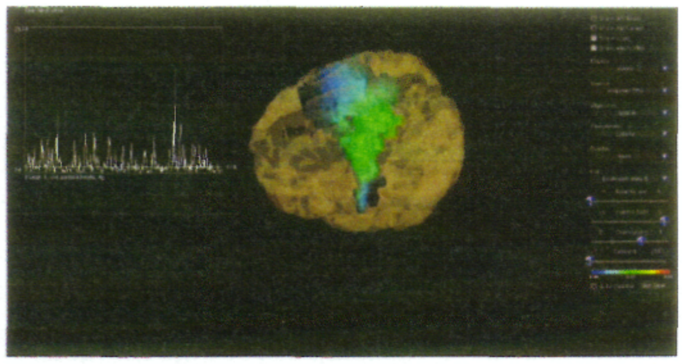

Figure 9: Example of sLORETA ROI training of Brodmann Area 6 (courtesy of Dr. Neils Schnepel)

- sLORETA has a guaranteed zero localization error, while LORETA has a non-zero localization error.
- sLORETA, like LORETA, contains ROIs and Brodmann Areas.
- sLORETA has more voxels per Region of Interest, hence provides higher spatial resolution.

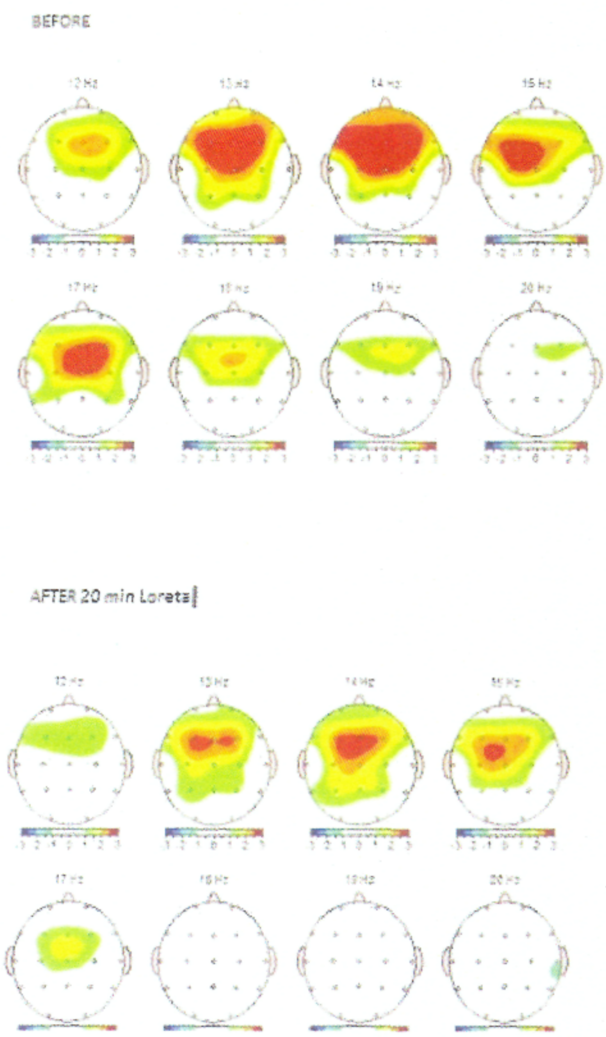

Figure 10: Pre and post QEEG's showing effects of 20-minutes of LLP training, Brodmann Area 4, 12-20 Hz.

- sLORETA is based on the same basic theory as LORETA, but reduce its sensitivity to noise. It has been extensively validated against MRI and other direct imaging methods, particularly with regard to its zero-localization error.

In the BrainAvatar, each voxel is converted into a current source density, and three spatial values (vectors) that describe the dipole. These spatial components are also relevant to connectivity. Each voxel represents an "analog" number, the local level of activity. In BrainAvatar, all projected signals are time-domain signals. This provides superior speed and accuracy, compared to FFT-based approaches, which introduce delays and possible distortion, due to the epoch size limitations. FFT-based methods also show only averaged activity, not instantaneous values. BrainAvatar computes the sLORETA projection using high-speed time-domain methods, and accurately shows the momentary changes in EEG signals. The combination of BrainMaster's high-speed digital filters with our unique projection technology provides the ability to compute hundreds of whole-brain sLORETA projections per second, and image and train on the data. Trained data can be from voxels or Regions of Interest (ROIs). All values are available though the flexible Event Wizard interface, so that an entire sLORETA training protocol can be inserted with a single, very simple event. An example of ROI training using the occipital area is shown in Figure 8.

The LLP system is also interfaced with the built-in JFTA and quadrature digital filter system, using up to 16 different frequency bands. In BrainAvatar, frequency-based training does not depend on FFT or related transform techniques. These can introduce delays, and require an "epoch" in order to process the frequency data with adequate resolution. Rather, all sLORETA projection in this system is done in the time-domain, on live filtered data. This means that, when imaging an alpha wave, for example, each and every cycle of every wave is processed and imaged, one sample at a time. This preserves phase information as well, and means that the sLORETA projector has access to individual wave events as quickly as possible.

There are many ways to use this data, as this is a toolkit, integrated with all of our existing software, including the Event Wizard. Figure 9 shows a design used by Dr. Neils Schnepel, training down 12-20 Hz on Brodmann Area 4. The pre/post QEEG maps show the effects of a single 20-minute session:

BrainAvatar sLORETA ROI and Voxel Training

- Based upon 88 ROIs
- Can train any band, any ROI
- Resolves and combines every voxel in ROI
- Each voxel or ROI provides a CONTINUOUS variable
- Event Wizard Interface
- Fixed or dynamic thresholds

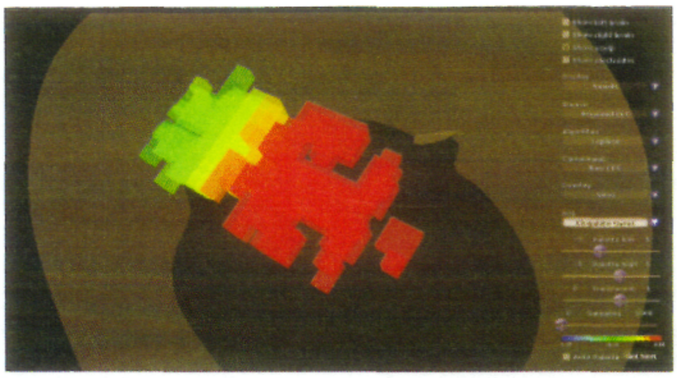

Figure 11: LLP zoom on cingulate gyrus, individual voxel activity shown in real time.

- Combine any number of ROIs
- Simultaneous display of ROI on screen
- 30 msec maximum delay from EEG event to screen or sound

The sLORETA LLP interface training software is user programmable, and provides a wide range of options.

- The individual source density for any voxel or voxels can be read out and used directly.
- The combined source density amplitude for all voxels in an ROI can be measured.
- Dipole moments of individual voxels or ROIs can be measured and imaged.
- The number of voxels in an ROI that meet a z-score criterion can be counted and trained.
- The number of voxels in an ROI that meet any other criterion can be counted or trained.

LLP feedback does not depend on a simple on/off response for a voxel or ROI; it provides continuous, proportional data. In addition, many types of on/off features can be defined.

With the LLP, it is possible to do multivariate proportional feedback, such as Percent Z-OK (PZOK) (Collura, 2008a, 2008b; Collura et al., 2009; Collura et al., 2010; Festa et al., 2009) on ROI. The practitioner can look at theta in the posterior cingulate, for example, and get a training variable that represents the percent of voxels in that ROI that meet a criterion or evaluate and train total and average activity of the entire ROI on a representative basis. If a clinician wants to select a single voxel, that can be measured and trained as well, using the Event Wizard.

Although live z-scores can be imaged and trained using various reference sources, BrainAvatar does not depend on z-scores to image brain activity. The LLP provides raw brain activation data, showing *what is* happening, not *what is not* happening. As noted by Leslie Sherlin (2009, p. 94), when one understands EEG and brain processes, it is not necessary to use normative z-scores in order to view and assess LORETA data. Raw data are an important dimension of visualizing brain activity when imaged in this way. BrainAvatar provides raw EEG-based brain electrical imaging, as well as the ability to visualize changes or differences when compared to other references. Those references could be normal but do not have to be normal. They could even be better than normal.

LLP neurofeedback is qualitatively different from any previous forms of neurofeedback. This is the first implementation that gives the trainee a complete, instantaneous, 3-dimensional view of his or her own

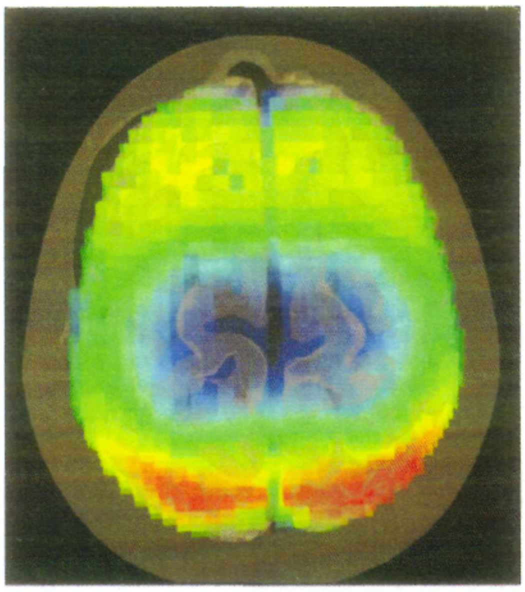

Figure 12: "Mini" Live sLORETA Projection using F3, F4, C3, and C4. This reveals the degree of asymmetry and anterior-posterior energy, showing regionalization of activity.

brain in real time. The speed of the feedback is at video speeds, so there is no sense of delay or waiting for the response to build up. While the feedback mechanism can include criteria such as sustained reward interval or refractory period, the visual rendering of brain activity is instantaneous and detailed. The LLP display can also be zoomed in, so that the ROI fills the screen, or even a handful of voxels are visible. The impact of seeing the anterior cingulated up close and magnified, and in real time, helps to understand the difference that this technology makes.

Generally, the LLP will require a cap or 19 free electrodes for LLP projections. However, it is possible to image and train a portion of the brain with as few as 12 or 14 channels, if only a specific region is of interest. BrainAvatar will include the ability to train on subsets of the full 19 channels, as well as the superset that adds Oz and/or FPz, for improved accuracy at the anterior and posterior midline areas. We anticipate that a 13-channel hookup leaving off Fp1, Fp2, F3, F4, F7, and F8, for example, may facilitate posterior training, without being affected by eye blinks.

Z-Builder is a tool to construct and train norms for scalp EEG parameters, sLORETA ROI and individual voxel parameters. Other possibilities include defining and training individual ROIs using Telaraich coordinates and gathering individual normative parameters for any ROIs to construct individual databases and test hypotheses. It is possible to store any client's EEG parameters and use them for long-term studies to follow up on the changes through aging. This way the client's healthy EEG can be used as an individual z-score reference to work on reversing deficits. This approach has been used in controlled studies at Brown University (Festa et al., 2009), in which cognitive decline was effectively arrested by using z-score neurofeedback.

Other possible applications are recording clients' brain activity under different conditions such as relaxation, reading, and speaking, or observing the changes during interventions, and their reactions to tasks.

The data regarding voxel dipole moments and vector components is an important new dimension in neurofeedback. These parameters are relevant to the pattern of pyramidal cell dipolarization in each voxel, as well as connectivity factors. Different vector components reflect different connectivities, hence provide a new way to assess and train brain connectivity, using sLORETA voxel data.

When used with less than 19 channels, the LLP provides information that is related to regionalization, if not complete localization. For example, Figure 12 shows a projection achieved using only 4 sensors, F3, F4, P3, and P4. Although the central and peripheral areas of the brain are not represented, this image nonetheless makes it possible to image the amount and type of activity in the four major lobes, which are covered by the sensors.

Template-Based Training with Z-Builder

In addition to what has now become the standard in normative live z-score training, this system now adds a new concept, that of template-based training. Template-based training is based upon the client's or someone else's actual QEEG profile, which can be used to create training protocols tailored to each specific client. While this is still live z-score imaging and training, the reference is no longer necessarily normal. It can be any type of individual, in any state, including the client's own reference state, or a different individual, for peak-performance or optimal functioning training.

Rather than training all clients to the norm, a clinician could train a client toward a modified version of their own QEEG profile. Components including power and connectivity can be trained across all 24 channels, or using sLORETA voxels or ROIs in any manner one chooses. Amplitude training, coherence training, synchrony training, bipolar training based upon the client's pre-existing brain dynamics, and selectively training the desired changes are combinable. Client QEEGs can be analyzed under any of a number of systems including NeuroGuide, NewMind, WinEEG, SKIL, EEGLab, or custom software, and the findings used to design the client's training protocol, independent of the database can be used for assessment. Now, Live Z-Score training can be done with or without a real-time normative database, increasing flexibility and reducing software expense.

Task-mapped training (or change training) is based on a similar concept; a recording is taken of the client's EEG (any number of channels), which is instantly converted into QEEG parameters, now those parameters are used as the reference for LLP projection or live Z-Score training. The client can be trained with z-scores based upon his or her own baseline, which serves as normal. The personalized z-scores can be compared to database-established z-scores even during training.

Changes during any task condition can be seen in QEEG instantly; components that do not change significantly will not be shown. This allows practitioners to see only the regions and frequencies that respond to the task condition, revealing underlying brain dynamics in relation to learning, memory, or other clinical concerns. When used with guided visualization, hypnosis, or related methods, the client's response to the work can be shown in precise and clinically valid QEEG terms.

Using the Event Wizard and the BrainAvatar LLP interface, clinicians can design protocols immediately, with almost limitless possibilities. Live sLORETA training can be combined with any existing protocols. You can do SMR, alpha, Infra-Slow, Slow-cortical potential, synchrony, or any other training along with the live sLORETA projector and analysis. Peripherals can be used such as Heart Rate Variability, skin conductance, EMG, respiration, or others along with the sLORETA, as well. BrainAvatar pushes the mind-brain connection, to provide a mind-brain-body connection for research or biofeedback.

Possible protocols could be:

- Train the anterior cingulate gyrus to increase its beta activity.
- Train down theta and uptrain beta in the anterior cingulate.
- Train "C3 beta/C4 SMR" using the sensorimotor cortex, not just the EEG sites.
- Train down theta in the anterior cingulate and train up beta in the posterior cingulate.
- Train the dorsolateral frontal lobes to have more beta than the ventromedial frontal lobes.
- Reward alpha activity from the frontal area, if it occurs after a posterior alpha burst.
- Implement an asymmetry protocol between any two ROIs; that is, train (ROI1 - ROI2)/ (ROI1 + ROI2). Rather than depending on F3-Cz and F4-Cz as leads, you could use the relevant dorsolateral frontal lobe regions and train them directly.

sLORETA ROIs used in LLP

Frontal Lobe
Limbic Lobe
Occipital Lobe
Parietal Lobe
Sub-lobar
Temporal Lobe
Angular Gyrus
Anterior Cingulate
Cingulate Gyrus
Cuneus
Extra-Nuclear
Fusiform Gyrus
Inferior Frontal Gyrus
Inferior Occipital Gyrus
Inferior Parietal Lobule
Inferior Temporal Gyrus
Insula
Lingual Gyrus
Medial Frontal Gyrus
Middle Frontal Gyrus
Middle Occipital Gyrus
Middle Temporal Gyrus
Orbital Gyrus
Paracentral Lobule
Parahippocampal Gyrus
Postcentral Gyrus
Posterior Cingulate
Precentral Gyrus
Precuneus
Rectal Gyrus
Sub-Gyral
Subcallosal Gyrus
Superior Frontal Gyrus
Superior Occipital Gyrus
Superior Parietal Lobule
Superior Temporal Gyrus
Supramarginal Gyrus
Transverse Temporal Gyrus
Uncus
Brodmann areas 1-11, 13, 17-25, 27-47

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