

A Rationale and Model for Infra-Low Frequency Neurofeedback Training

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Summary:

We are in the midst of a scientific quest to understand the underpinnings of human behavior in the organization of our neural networks. The impact of our improved understanding is being felt both at the conceptual and the clinical level. Commonly, however, clinical developments precede an understanding of mechanisms. Such has been the case of neurofeedback, the roots of which go back some forty years. It is appropriate to assess that therapeutic approach in the light of current models of neuroregulation.

This article focuses on the relatively recent development of feedback on the dynamics of our slow cortical potentials, a therapeutic method that has shown itself to be highly effective in addressing even severe psychopathologies. This development needs to be seen in the context of the prior history of neurofeedback. It also needs to be illuminated by the latest findings on the structural and functional organization of our core regulatory networks.

History of the Development of Infra-Low Frequency Neurofeedback

Since its discovery in 2006, neurofeedback in the infra-low frequency (ILF) region of the EEG spectrum (below 0.1 Hz) has quickly matured into a therapeutic method applicable to the full spectrum of mental disorders. The striking clinical results that have been obtained raise the question about what mechanisms could account for the apparent potency of this method. That topic will be briefly addressed in the following.

The discussion is best introduced by consideration of the context out of which infra-low frequency neurofeedback first emerged. There were three principal influences on this development: existing frequency-based training strategies, reinforcement on slow cortical potentials, and traditional biofeedback using measures of peripheral physiology.

Classical Frequency-band Training

ILF training emerged out of traditional frequency-based neurofeedback that has existed since the early 1970s. Here the principal targets of training were the resting frequencies of our sensory systems, 10 Hz in the case of the visual system (the famous alpha rhythm) (Hardt & Kamiya, 1978), and 13 Hz in the case of the motor system (called the Sensorimotor Rhythm or SMR) (Sternan, Howe, & MacDonald, 1970). The immediate objective was the calming of arousal level with alpha training, and the reduction of motoric excitability with SMR training.

The training procedure relies on the principles of operant conditioning. Thresholds are set on amplitude in the training band, and 'rewards' are given when thresholds are exceeded. The fluctuating amplitude might, for example, be represented as the size of a graphical object in a video image. Whenever the size of the object exceeds the threshold, which is also illustrated, success could be signaled with a pleasant tone. The tone would be repeated regularly as long as the reward criterion was met. Over time, the feedback was incorporated in ever more varied video animations. In a parallel path, the brain is also cued with respect to excursions into disregulation as these are detected in the real-time broadband EEG.

The alpha-training tended to be used with anxiety conditions and addictions (Moore, 2000; Passini et al., 1977; Peniston & Kulkosky, 1989). The sensorimotor rhythm training matured in application to seizure management (Sternan, 2000) and the ADHD spectrum (Lubar et al., 1995). In this manner, a divergence emerged over time in which Alpha-Theta training became associated with conditions that had a substantial psychological component, whereas SMR-beta training came to be associated with physiological normalization. (Beta here refers to the beta1 band of 15-18Hz.)

Documentation of Efficacy of Frequency-band Training

As already indicated, neurofeedback has matured largely through clinical work at the hands of clinicians. Many formal research studies now exist and neurofeedback publications are growing at an exponential rate, as shown in **Figure 1**. Meta-analyses for ADHD (Arns et al., 2009) and seizure disorders (Tan et al., 2009) testify to the efficacy of the method, and several controlled studies document the effectiveness of including neurofeedback in addiction treatment (Peniston & Kulkosky, 1995; Scott et al., 2005). Multiple publications exist for conditions covering the range from the anxiety spectrum and sleep disorders to migraine (Stokes, 2010; Walker, 2011), tic disorders, tinnitus (Dohrmann et al., 2007), traumatic brain injury, the autistic spectrum, and even schizophrenia.

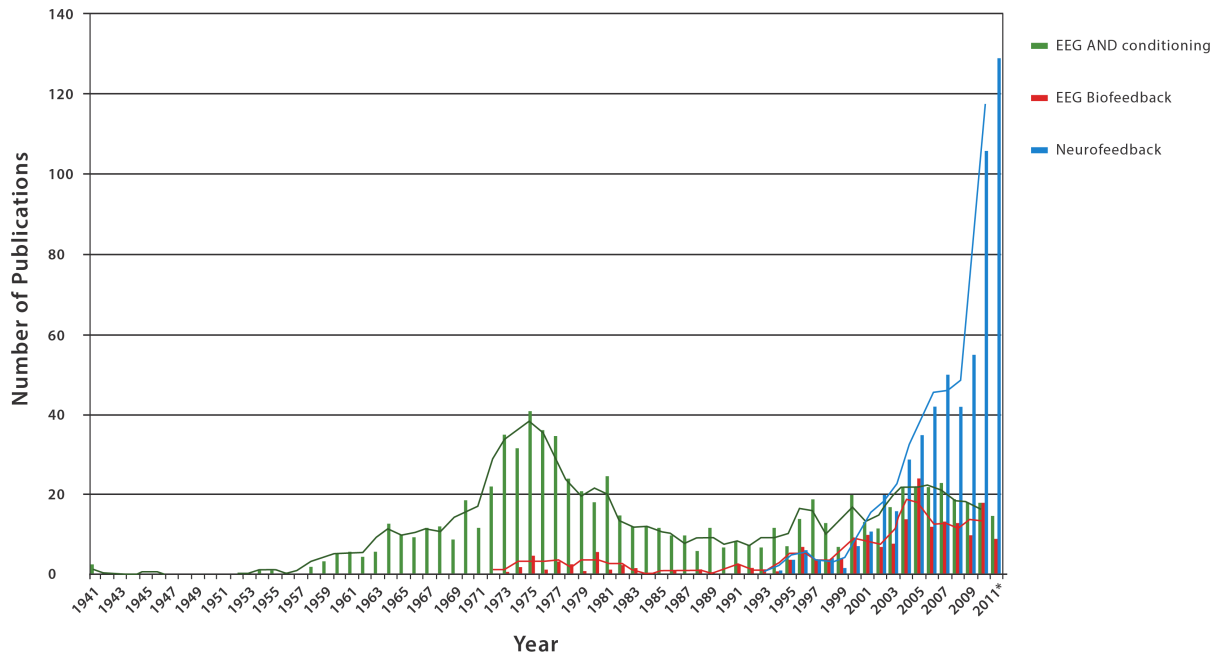


Figure 1: Incidence of key words related to neurofeedback in the scientific literature.

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SCP-Neurofeedback: Training on the slow cortical potential

When the frontier of the infra-low frequency region was first breached with frequency-based feedback, this was done in full awareness of the many years of research by Niels Birbaumer and his group at Tübingen on the training of slow cortical potentials (SCP) (Birbaumer et al., 1990; Birbaumer, 1999). That work had already established the essential utility of training solely on information derived from the slow cortical potential. Moreover, the clinical findings with that method tended to correspond with those obtained with frequency-band training: seizure management (Sterman, 2000; Kotchoubey et al., 2001), ADHD (Lubar et al., 1995; Strehl et al., 2006), and migraine (Siniatchkin et al., 2000; Walker, 2011). Similar objectives were being achieved with two radically different methods.

Even though SCP training and ILF training operate in overlapping frequency domains, the actual procedure differs greatly between the two approaches. It was not known how much one could rely upon the slow cortical potential, as there are obviously non-neuronal influences in play. In SCP training, a trainee is tasked to deliberately increase or decrease the ambient SCP signal within the short time frame of 8 seconds, which necessarily engages neuronal mechanisms. Bilateral control was sought in order to demonstrate mastery with respect to the voluntary control of neuronal excitability (Elbert, 1993). Significantly, the baseline level of the SCP was not explicitly relevant in this process. ILF training, on the other hand, involves an even slower time frame in which the trainee merely witnesses the signal without a mandate to try to change it.

Peripheral Biofeedback

The development of ILF training also unfolded in awareness of the complete repertoire of training approaches in traditional biofeedback, in which measures of peripheral physiology (skin conductance, hand temperature, muscle tension, heart rate variability, etc.) are used to cue the brain toward better-regulated states through reinforcement procedures (Schwartz & Andrasik, 2003). The immediate objective in these methods is to train the autonomic nervous system toward better regulation, and this has beneficial fallout for emotional regulation and arousal regulation as well. That in turn, has positive implications for pain syndromes, the anxiety-depression spectrum, and sleep dysregulation in particular.

Multiple Pathways to Self-Regulation

The above precursor technologies have already answered a number of key questions. With peripheral biofeedback, it was established firmly that sustained improvements in self-regulation status can be achieved. This proved that learning must occur as a consequence of the reinforcements. With frequency-based neurofeedback, it was established that aspects of executive function, attentional mechanisms, and motor control can be trained, and that the beneficial effects are retained over the long term. These effects are achieved with very frequency-specific training, which means that distinct neuronal networks are engaged in this process. In 2005 the journal *Child and Adolescent Psychiatric Clinics of North America* devoted an entire issue to neurofeedback, under the theme of Emerging Interventions (Hirshberg et al., 2005). And finally, the training of slow cortical potentials (SCP) demonstrated that neuronal networks may be reorganized with reinforcements derived entirely from low-frequency information.

Preconditions for the emergence of Infra-Low Frequency Training

The above state of affairs still leaves a number of gaps in the narrative about how the new infra-low frequency training came about. After all, the new method is the direct descendant of traditional frequency-based training, which was oriented toward working with fixed frequency bands. The new developments are traceable to three key factors. First, feedback was given on the real-time dynamics of the training band, and not merely on the threshold crossings. This means that in the feedback animation, the amplitude function was continuously represented in its ebb and flow, through variation in game-play often depicted by the movements of a car or rocket or jet-ski. The particulars are illustrated in **Figure 2**, where the various stages of signal processing are illustrated. Continuous information about the signal made the training much more sensitive to the arousal state of the trainee. The change in state was then also more likely to impinge upon the awareness of the client. Second, bipolar montage was adopted so that the training was based on the relationship between two cortical sites. This brought network relations to the fore in the training.

These two particulars set the stage for the most critical factor, the adoption of a frequency-optimization strategy with every training session. With each client there was an ongoing attempt to optimize the procedure with fine-tuning of the reinforcement frequency. Quite early in this development, it was found to be advantageous to tune the reward frequency to within 0.5 Hz. This level of discrimination of

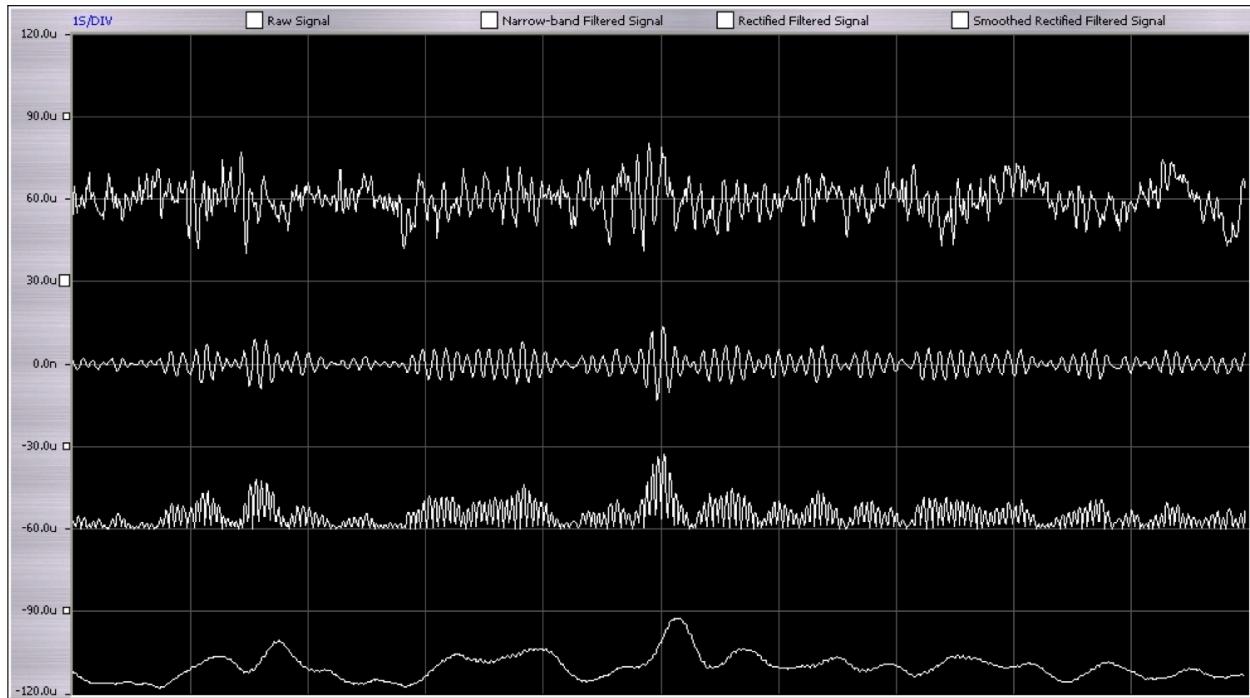


Figure 2: Signal processing steps illustrated for SMR-band (12-15Hz) training: The top trace shows the raw EEG signal in the bandpass from 0.5 to 30 Hz; the second trace shows the same signal bandpass-filtered at 12-15 Hz to accentuate the SMR-band signal; the third trace shows the same signal rectified; the bottom trace shows that same signal digitally smoothed for thresholding. These data were recorded on the NeuroCybernetics, our original computerized instrumentation for SMR-beta training (1987).

the signal was difficult to believe in the abstract, as the neighboring signals don't look very different. This is illustrated in **Figure 3** with three filtered traces derived from the same source signal, each separated by 0.5 Hz from its neighbor. One is hard-pressed to see a difference in the three signals. If, on the other hand, the same waveforms are shown as spectral plots, the differences between them become more apparent. The compressed spectral arrays are shown in **Figure 4**. This prompts us to consider that the brain's appraisal of the signal may also rest on a frequency domain representation.

The arousal level dependence on target frequency allowed the effects of the reinforcements to be observed within session in terms of shifts in the state of alertness and of emotional ambience. Fortuitously, the target frequency that leads to the best-regulated state within the training session is also the right frequency for best outcome. Sometimes it is difficult to discern the optimal frequency, and then one must orient mainly to the post-session changes.

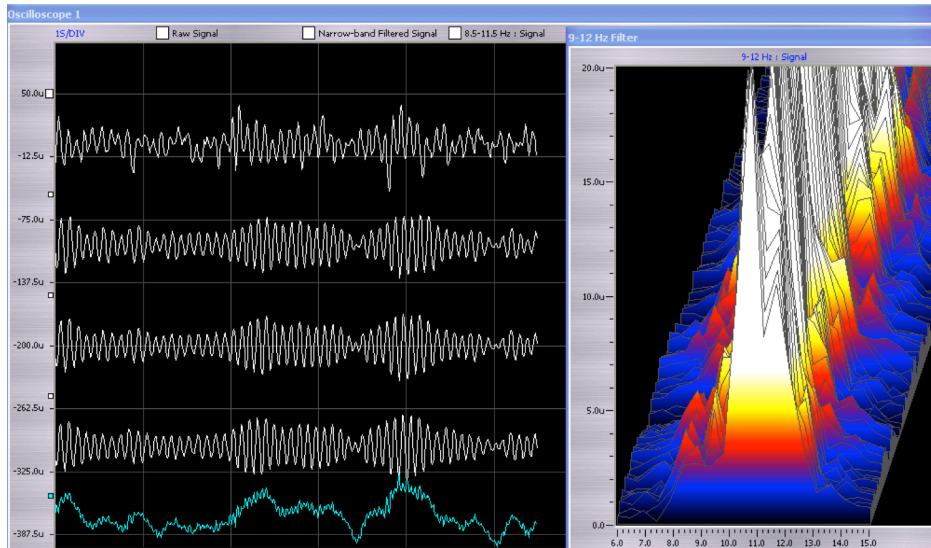


Figure 3: Three filtered traces derived from the same source, with center frequencies spaced 0.5 Hz apart, at 9.5 Hz, 10 Hz, and 10.5 Hz, respectively. It is difficult to tell the time domain signals apart by inspection, and yet the brain may experience them differently. The compressed spectral array is shown on the right for one of the traces.

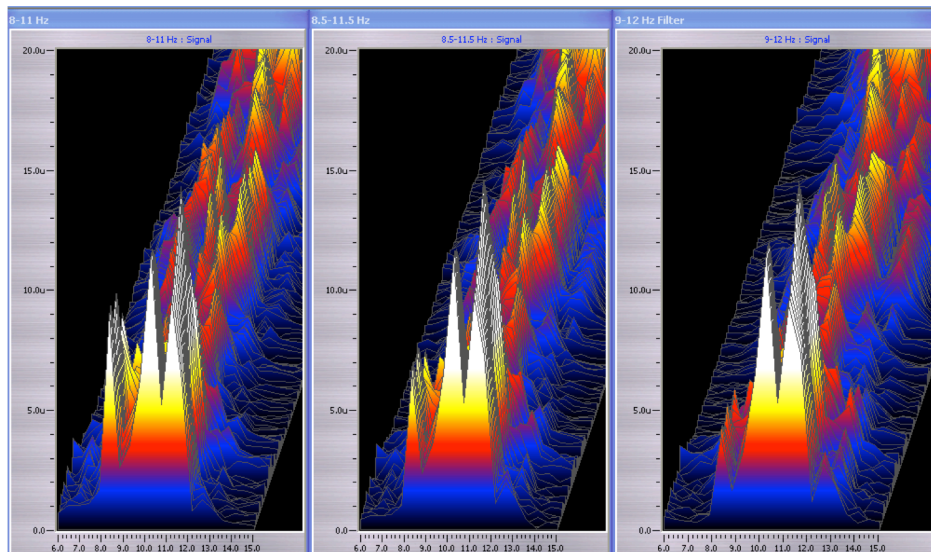


Figure 4: Three Spectrograms for the three filtered traces of Figure 3. In the frequency domain representation, it is easier to tell the difference between the three signals. This is a clue that perhaps the brain's appraisal of the signal should likewise be viewed in the frequency domain perspective.

A Shift in the Neurofeedback Paradigm

Conceptual Barriers

The optimization strategy opened up the parameter space so that training effectiveness could be evaluated over a wider range of target frequencies. Over time, this led ineluctably to the finding that the more challenging clients tended to optimize at lower frequencies than the healthier clients. Over the course of years the EEG frequency domain was therefore increasingly explored in the direction of ever lower frequencies. The time frame here was 1996 to 2006, by which time training had extended to include the bandpass of 0-3 Hz.

Eventually it became necessary to broach the domain below 0.1 Hz, the infra-low frequency region. This occurred in 2006 (Othmer, 2006). The barrier to this development was frankly a conceptual one. Amplitude-based training was out of the question at such low frequencies. The alternative was just to allow the brain to observe the time course of the unfolding real-time signal. This is shown in **Figure 5** for a filter set at one milliHertz center frequency. The trainee gets to witness the rise and fall of the quasi-periodic waveform, much as he might watch the ocean swells rolling toward the shore at the beach. This meant the abandonment of any kind of thresholding, and that in turn meant we were giving the brain no guidance with respect to the desired direction of change. With this transition, the traditional operant conditioning model had to be jettisoned. That had been the conceptual barrier.

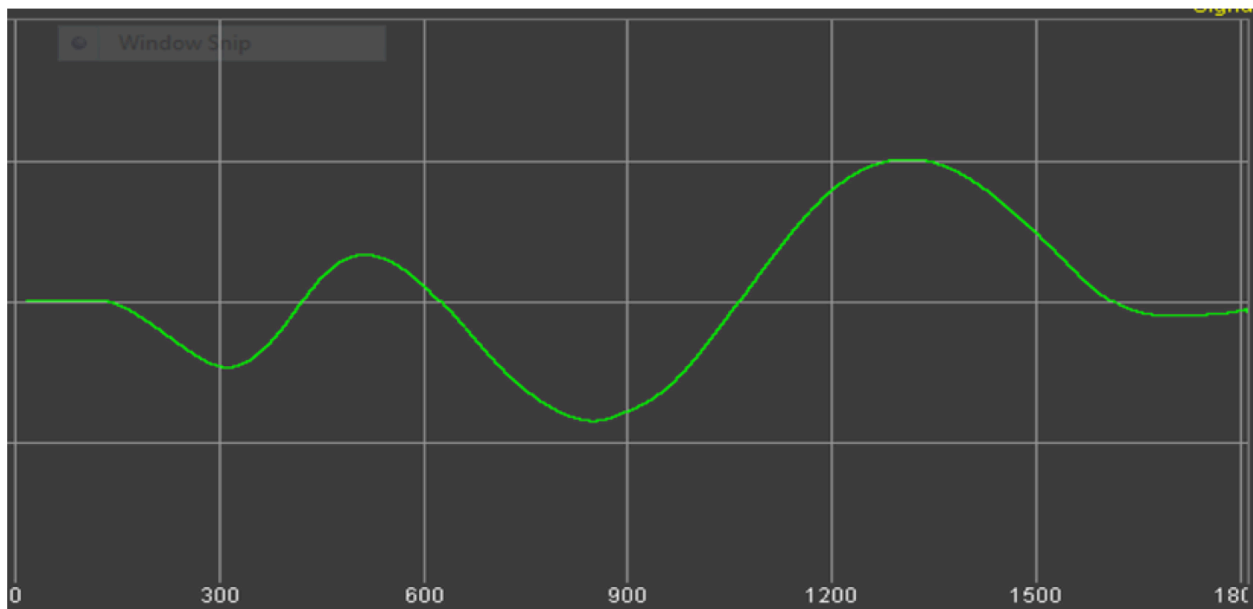


Figure 5: Filtered EEG waveform for a filter centered at 1 milli-Hz. The onset of signal capture occurs at 150 sec into the record. Roughly two full cycles are displayed in a 30-minute session.

The Dispensable Threshold

It became apparent at once that the brain responds to this information about its own band-limited slow cortical potentials rather immediately and specifically. The brain did not need thresholds to guide the process; it just needed sufficient information. With the brain now able to witness the entire time course of the signal, the training became even more frequency-sensitive than we had observed at the higher bands. The implication was that the SCP could be trusted to guide the training. From the clinical perspective, the essential character of the training remained the same. Qualitatively everything behaved as before, only the results were more satisfying in various ways, and were being obtained more consistently.

Clinical Effectiveness Guides Training

Over time, the optimization strategy took us to the extremely low frequencies of 0.1 to 1.0 milli-Hz (mHz), in the range of our basic ultradian rhythms. The impetus all along was the observation that clinical outcomes tended to improve, and were more broadly available, at these lower frequencies. Challenging clients, who did not yield to the higher-frequency training, were responding.

And therein lies the mystery. How can going to lower frequencies lead to better and quicker results? If we regard the whole feedback loop of the client engaged with information on his own EEG from the standpoint of information theory, then we are providing less information per unit time as we restrict our attentions to ever lower frequencies. At the same time we are observing responses on the part of the client just as quickly as ever, over the course of minutes. And the training is as frequency-sensitive as anywhere else on the spectrum, if not more so.

The Brain Encounters Itself in a New Feedback Loop

The observed rapid response, particularly in the context of high frequency-specificity, appears to be inconsistent with our focusing only on extremely slow signals. In particular, the brain can detect differences between two nearby frequencies (say 0.9 and 1.0mHz) quite readily and quickly (i.e., over three to five minutes.) An external observer would have to see the signal unfold over an extended period of time in order to distinguish cleanly between those same two frequencies. And even that discrimination could only be made if the signals were cleanly sinusoidal, which is not the case for the fluctuations in the slow cortical potential.

The only way to understand this entire process is to regard it from the standpoint of the brain as the experiencing entity. The signal is of interest only to the brain that gave rise to it. And fortunately the brain recognizes its connection with the signal even when the signal is very slow. Once the connection is recognized, the brain takes responsibility for the signal and tries to steer it. This is a natural process, like the brain taking charge of the handlebars of a bicycle or the steering wheel of a car even while the driver's thoughts are directed elsewhere. The brain just adds this new control loop to its repertoire of continuous, ongoing responsibilities.

With this shift in perspective, everything now falls into place. With a slight shift in frequency response, the brain's experience of the signal starts to be slightly different almost immediately, and the brain will start responding accordingly. That can indeed happen quite rapidly. The brain is aware of two realities that are observed to be correlated. One is the external signal on the screen and the other is its internal state of activation at the site of the electrodes. As soon as the frequency of detection is altered, that relationship changes, and with it the reaction of the brain. The initial response of the brain to the altered circumstances is in accord with the interpretive template that already exists. That template necessarily adapts more slowly, but also on the time constant of a few minutes. The point is that rapid response to the novel circumstance is not ruled out, even though we are working in an extremely low frequency band.

The above description conveniently refers to the brain in anthropomorphic terms. It remains to translate those concepts into the language of neurophysiology. There is no entity or locus within the brain that can claim observer status with respect to itself. There is no homunculus. Strictly speaking, the brain's 'experience' is restricted to interacting neural networks. The transit of the signal on the screen has a particular neural representation, and that happens to be correlated with the ebb and flow of cortical activation at a specific cortical site (or more correctly, the relative activation trends between two cortical sites). Activation plays directly into the neuronal dance at each site. Our neural organization is geared toward correlation detection and pattern recognition. The very fact that infra-low frequency neurofeedback works at all is powerful testimony to the exquisite capacity of our neural networks to perform such correlation tasks. Pattern recognition is manifestly possible even under the limiting conditions of a very slow-moving--- and therefore relatively featureless---signal.

The observation that infra-low frequency training works more quickly and more effectively and has a broader impact than the same methods applied at higher EEG frequencies requires a different explanation. One is compelled to conclude that the information provided at the lowest frequencies must be more salient to the brain in the context of the given task of improving self-regulatory capacity. This is not entirely surprising, as the objective is to train the mechanisms that organize the brain's persistent states. This leads one to conclude that the infra-low frequency training must be facilitating the re-organization of the functional connectivity of our resting state networks.

The Resting State Networks

As it happens, the discovery of our brain's resting state networks was made on the basis of correlational studies with functional magnetic resonance imaging (Biswal, 1995). Ironically, the discovery was facilitated by the fact that the fMRI signal can only reveal low-frequency information. In theory, the discovery of these networks could have been made in the conventional EEG domain, but that did not happen. The low-frequency patterns are best observed at low frequency. The same factor may be operative in the realm of neurofeedback: information available at low frequency may be particularly useful to guide the re-organization of resting state networks.

The term *resting state networks* is historically well established, but may be a bit of a misnomer. Reference is primarily to the Default Mode Network, where our brains linger when not being externally

challenged (Raichle et al., 2001; Raichle, 2010). Upon being presented with the need to engage, the brain shifts toward the 'task-positive' networks, the Dorsal Attention Network and the Central Executive Network. Mediating the interaction between the Default Mode and the Central Executive Network is the Salience Network (Sridharan et al., 2008). Jointly the above constitute our 'base set' of principal control networks.

What tends to be obscured in the discussions is the fact that the Default Mode Network is comparably active during engaged states. Hence the quality of Default Mode Network internal functional connectivity is foundational to the entire enterprise of enhancing self-regulatory capacities. Indeed, every one of the key montages utilized in our implementation of infra-low frequency training targets principal nodes in the Default Mode Network, the Salience Network, and the Central Executive Network.

Significantly, every one of these principal placements was arrived at empirically, through the clinical optimization procedure, independent of knowledge of the Default Mode Network structure. Hence the match-up with Default Mode hubs may be considered an independent validation of the optimization procedure. A systems perspective governed the search for the most propitious electrode placements. The inter-hemispheric placement T3-T4 serves the purpose of promoting brain stability, as indexed by the incidence of seizures, migraines, panic attacks, and bipolar excursions. This corresponds to the primary linkage in the Default Mode between the left and right lateral temporal cortices (Buckner, 2008).

The regulation of central arousal level is most efficiently effected at T4-P4. This corresponds to the key linkage in the Default Mode between the right lateral temporal cortex and the right inferior parietal lobule. Emotional calming is achieved most efficiently with T4-Fp2, which links the right insula with the pre-frontal region, the key hubs of the salience network. It should be noted that all of the key placements are located at the highest levels of functional organization for the respective regions: the multi-modal association areas. These are last to mature and the first to degrade under the stresses of aging. They were also the last to develop phylogenetically, and they presumably lend themselves most readily to adaptive learning. Brain stability and arousal regulation are the first targets of training, and rely principally on the above placements.

To complete the picture, it has been proposed that a number of psychiatric conditions are characterized by significant deviations in the functional connectivity of the control networks (Broyd et al., 2009; Menon, 2011). The list includes Autism, Schizophrenia, Fronto-Temporal Dementia, ADHD, and PTSD. It is easy to surmise that the findings to date point to a general principle that the psychopathologies are largely traceable to disruptions or dysregulations in the intrinsic properties and the mutual integration of our core connectivity networks. Infra-low frequency neurofeedback may then constitute an efficient means of restoring more appropriate regulation. In principle this could also be accomplished with fMRI feedback, however this would clearly limit clinical access and affordability. The first publications that demonstrate the connection of neurofeedback with the regulation of the resting state networks are currently available for both conventional frequency-domain neurofeedback (Ros et al., 2013) and fMRI neurofeedback (Van de Ville et al., 2012).

Finally, it should be observed that the clinical exploitation of ILF training has led us to the establishment of a fundamental relationship between the optimal target frequencies in the left and right hemispheres. This relationship is illustrated in **Figure 6**. The relationships hold over the entire frequency range from 0.1mHz to 40Hz. They therefore point to a fundamental organizational principle governing functional connectivity.

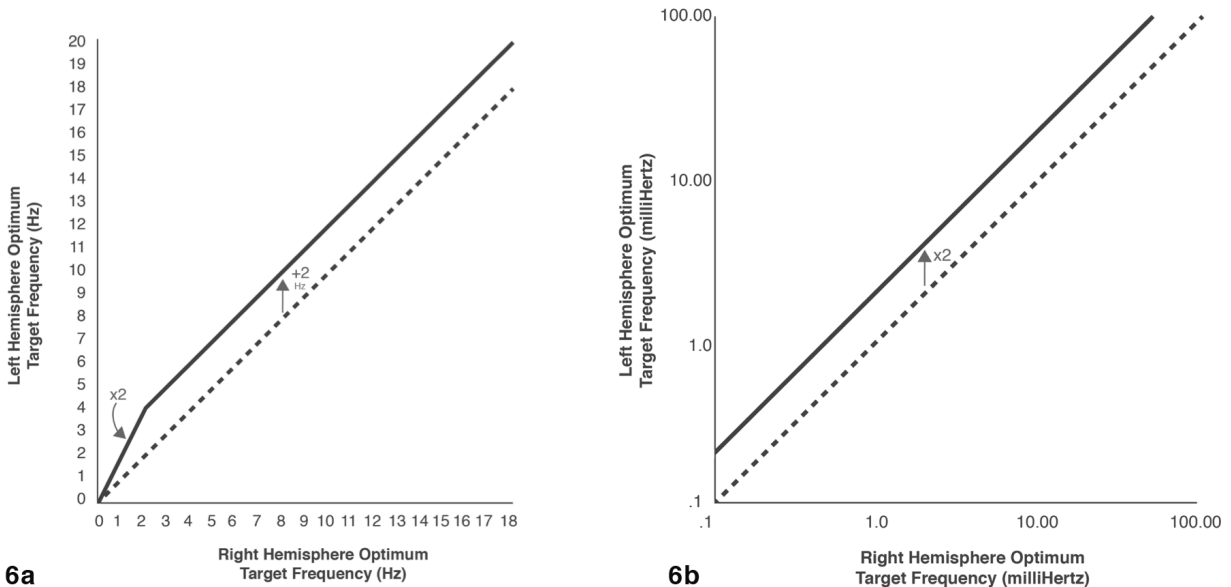


Figure 6: (a) A fixed relationship prevails between the optimum response frequencies in the left and right hemispheres. In the EEG range above two Hz, the left hemisphere training optimizes at two Hertz higher than the right. Below two Hz, the relationship is geometric. The left hemisphere training optimizes at twice the frequency of the right. (b) The frequency relationship between the left and right hemisphere is illustrated here in a logarithmic plot, showing that the relationship is invariant over the entire infra-low frequency range with which we are now engaged.

In summary, basic mechanisms have been proposed for the broad utility of infra-low frequency neurofeedback training in remediating psychopathologies and neurological dysfunctions. All of the therapies discussed have in common a bias toward lowering of the arousal level, commonly referred to as relaxation training. The infra-low frequency training offers a means of actively engaging the brain in the task of functional renormalization under such favorable conditions.

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