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SPECTRUM-WEIGHTED EEG FREQUENCY ("BRAIN-RATE") AS A QUANTITATIVE INDICATOR OF MENTAL AROUSAL

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Abstract: A concept of brain-rate is introduced, defining it as the weighted mean frequency of the EEG spectrum. In analogue to the blood pressure, heart-rate and temperature, used as standard preliminary indicators of corresponding general bodily activations, it is proposed to use the brain-rate as a preliminary indicator of general mental activation (mental arousal) level. In addition, along with the more specific few-band biofeedback parameters (theta-beta ratio, relative beta ratio, etc.), the brain-rate could be effectively used as a general multiband biofeedback parameter.

Key words: EEG, mental states, arousal, neurofeedback, brain-rate

Introduction

It is a well-known empirical fact that mental arousal, defined as the "general activation of the mind" [1], is related to EEG frequency (see Fig. 1 below).

This correlation between the brain frequencies and the mental states is the starting-point of EEG biofeedback (neurofeedback) treatment. In general, biofeedback (central or perpherial) means feeding back biosignals, aimed at achieving self-control by operant conditioning. As a central biofeedback modality, neurofeedback is based on elevation/suppression of certain pre-chosen EEG frequency bands [2–6]. Consequently, different indicators (e.g. theta-beta ratio, relative beta ratio, etc.) have been used as biofeedback parameters.

However, in reality whenever some bands are modulated, the others are influenced too. In what follows, a complementary biofeedback parameter, characterizing the shift (hardening or softening) of the whole EEG spectrum, is introduced. The same indicator (termed "brain-rate") is proposed to be used for a preliminary check of general mental activation (mental arousal), along with heart-rate, blood pressure and temperature as standard measures of general bodily activation.

The concept of brain-rate

The basic dependence of mental arousal on EEG frequency, established empirically, is summarized in Fig. 1.

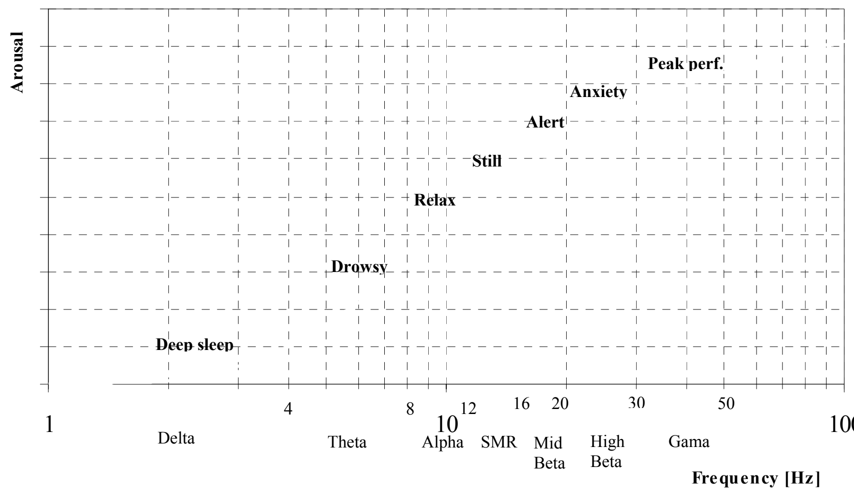

Figure 1 – *Standard classification of EEG activity and the mental states i.e. arousal (adapted from [7, 8]). Note log scale on the abscissa and absence of scale on the ordinate.*

There are no quantified empirical data about the mental arousal level, so that only the continuously increasing arousal trend, without specified values on the ordinate, is shown in Fig. 1, along with the corresponding frequency bands on the abscissa.

Actually, the theoretical explanation why the mental arousal is correlated to the electric field frequency, and why just in this way, is still missing. One possible approach to this problem, based on quantum transition probabilities has been developed recently [9, 10]. Starting from this approach, the following analytical expression for mental arousal level is derived [11]:

$$A = e^{-\frac{f_e}{f}\ln 2} = 2^{-\frac{f_e}{f}} \qquad (1)$$

where f_e is the equilibrium frequency, at which the entropy is maximal. Actually, this frequency corresponds to the dominant frequency with eyes closed, known to be age dependent (equal from around 6 to around 10, for children and adults respectively [12]).

Evidently, the graphical representation of the above formula appears to be in conformity with the empirical dependence shown in Fig. 1.

However, irrespective of the proposed quantum neurophysical hypothesis and the obtained concrete form of functional dependence of arousal (A) on the frequency (f), $A = A(f)$, we may ask how the value of the independent variable (argument of the function) could be determined. Bearing in mind the origin and the meaning of the empirical data presented in Fig. 1, the variable f, related to the dominant frequency band, can be identified as a spectrum-weighted mean frequency. Characterizing the EEG spectrum, it may serve as a quantitative indicator of the general brain activation, and we will term it "brain-rate" (in analogue to e.g. heart-rate). As such, it can contribute to the gross, initial assessment, not substituting the subtle, differential investigations of disorders corresponding to the same general level of arousal.

The algorithm for the brain-rate calculation

Being defined as the mean frequency of brain oscillations weighted over the all bands of the EEG potential (or power) spectrum, the brain-rate (f_{b}) may be calculated as:

$$f_{\mathrm{b}} = \sum_i f_i P_i = \sum_i f_i \frac{V_i}{V}, \qquad \text{with } V = \sum_i V_i \tag{2}$$

where the index i denotes the frequency band (for delta $i = 1$, for theta $i = 2$, etc.) and V_i is the corresponding mean amplitude of the electric potential. Following the standard five-band classification, one has $f_i = 2$, 6, 10, 14 and 18, respectively.

As can be seen, the formula for calculation of the brain-rate f_{b} is based on the same algorithm as that used for determining, for example, the center of gravity (or mass), or the mean energy (i.e. temperature) of a physical system. The analogy with the temperature is the most striking, both concepts being based on similar physical models. Namely, the temperature $\left(T = \frac{2}{3k}\sum_i E_i P_i\right)$ represents (in the case of three degrees of freedom) the mean energy weighted over the particle distribution spectrum (with P_i being the probability of having E_i), while the brain-rate $f_{\mathrm{b}} = \sum_i f_i \frac{V_i}{V}$ represents the mean EEG frequency weighted over the brain potential (or power) distribution spectrum. Specifically, in the case of neutron spectra, there are slow (thermal), medium (resonant) and fast (fission) regions, which can be compared with the slow (delta/theta), medium (alpha) and fast (SMR/beta) regions of the EEG spectrum. Despite the different contents, these analogies may suggest the use of similar mathematical representations.

Of course, a more precise calculation of f_b can be performed using the corresponding integral form, where the frequency bands are smeared up:

$$f_b = \frac{1}{V}\int fV(f)df, \qquad V = \int V(f)df \tag{3}$$

In order to illustrate clearly the comparison with the standard EEG and neurofeedback practice, in the following we use the eq. (2) based on the frequency bands (whose amplitudes are explicitly quantified by EEGs).

Brain-rate as a biofeedback parameter

As empirically confirmed, subjects with mental disorders and disabilities display an abnormal brain electric activity. For instance, based on numerous EEG as well as Quantitative EEG reports, it was concluded that "there is wide consensus that delta or theta excess and alpha and beta deficits are commonly encountered in children with learning disorders …" [13]. It is also important to mention that "if you want to change cortical functioning with neurofeedback you do not need to train 19 different locations, you can train one or two and the others will change in accordance with the dynamic resonant looping that is already set up in place" [14].

The conventional neurofeedback protocols use modulation of discrete frequency bands, assuming to be associated with frequency-specific mental states. In the case of Attention Deficit Hyperactivity Disorder (ADHD) this means elevation of beta and suppression of theta [2, 3, 6], or enhancement of absolute or relative low beta [4, 5]. Consequently, as biofeedback parameters the theta-beta ratios or relative low beta are used.

Still, in practice, whenever a certain band is trained, the other bands are affected too (it may even appear that e.g. "…the changes that occurred as a result of stimulating in the alpha frequency were not in alpha but were in beta…" [14]. Moreover, practically all neurofeedback interventions can be roughly reduced to the need of mastering flexibility in increasing or decreasing the general mental activation, i.e. mental arousal (which is somehow coupled with metabolic activity). Therefore, the introduced brain-rate f_b could be employed as a complementary biofeedback parameter, characterizing the whole EEG spectrum (as distinct from e.g. theta-beta ratio). The rationale is that, according to the mentioned empirical results, the EEG frequency shifts are related to mental activation/deactivation, as the main objective of the treatment.

Diagnostic limitations of brain-rate indicator

Using extensive clinical databases, some normative classifications of EEG patterns have been established, contributing to differential diagnosis and selection of treatment [e.g. 13]. A recent comprehensive review [15] identified 11 major groupings of EEG/QEEG findings, with the description of patterns and the recommendation for intervention (medication and neurofeedback).

Reviewing the mentioned list, it can be inferred that for nine patterns/phenotypes the proposed brain-rate f_b is applicable, both as a preliminary indicator and a biofeedback parameter. The two profiles where f_b cannot serve as a preliminary differentiating indicator are: "mixed fast and slow" and "epileptiform", since for these abnormalities there is a formal "compensation" of low and high frequencies. However, even in these cases, f_b can be used as a pertinent biofeedback parameter.

Some illustrative examples

A random example of brain-rate (f_b) calculation, using row EEG screen data for spectrum band potentials V_i, is shown in Table I.

Table I.

Calculation of brain-rate f_b (left: first 3.5 sec and right: whole session)

Band	f_i [Hz]	V_i [μV]	$f_i V_i / V$ [Hz]
δ	2	66.1	1.33
θ	6	12.2	0.74
α	10	13.4	1.35
SMR	14	5.4	0.76
β	18	2.3	0.42
		ΣV_i [μV]	f_b[Hz]
		99.4	4.59

Band	f_i [Hz]	V_i [μV]	$f_i V_i / V$ [Hz]
δ	2	7.37	0.39
θ	6	10.08	1.61
α	10	7.77	2.06
SMR	14	3.98	1.48
β	18	8.44	4.04
		ΣV_i [μV]	f_b[Hz]
		37.64	9.58

Data for EEG potentials (V_i) are taken from [16].

The age of the random example "sample John", presented in Table I, is not known. Anyway, the resulting f_b = 4.59 would correspond to a very drowsy state (or mental retardation) for an adult, and a relaxed state for a child, while f_b = 9.58 would correspond to a relaxed state for an adult, and a very attentive (or anxious) state for a child.

Analyzing some recent results of EEG biofeedback training in ADHD children [17], we found that the change in brain-rate f_b, showing the spectrum shift, appeared (in certain cases) to be a more realistic indicator of the change in clinical symptoms than the standard theta-beta ratio change. As an illustration, we present the cases of two school-boys (GL and DT) diagnosed with ADHD. Both were trained by 40 NF sessions – the first 20 sessions to elevate SMR and suppress theta, and the second 20 to elevate beta and suppress theta. As a result, for GL the theta-beta ratio had decreased while in the case of DT this ratio had slightly increased. However, according to clinical investigations and interviews with the teacher and parents, an improvement had been registered for both children, although this was less pronounced for the second one. The calculation of the brain-rate f_b in both cases showed higher values at the end of training. Moreover, the spectrum shift for the first child (GL) was twice as high as that for the second one (DT), which corresponds to the clinical and teacher/parent's assessments.

Conclusion

The introduced concept of brain-rate, representing the weighted mean frequency of the potential/power EEG spectrum, may serve as a preliminary indicator of general mental activation (mental arousal) level, similar to blood pressure, heart-rate and temperature used as standard preliminary indicators of corresponding general bodily activations.

Characterizing the EEG spectrum shift, the brain-rate could be effectively used as a general multiband biofeedback parameter, along with the more specific few-band parameters.

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Р е з и м е

СПЕКТРАЛНО-УСРЕДНЕТА ЕЕГ ФРЕКВЕНЦИЈА („МОЗОЧНА БРЗИНА“) КАКО КВАНТИВЕН ИНДИКАТОР НА МЕНТАЛНА ПОБУДЕНОСТ

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Воведен е концепт на мозочна брзина, дефинирајќи ја како тежински усреднета фреквенција на ЕЕГ спектарот. Предложено е таа да служи како прелиминарен индикатор за нивото на општата ментална активација (ментална побуденост), слично на крвен притисок, срцева брзина и температура, користени како стандардни прелиминарни индикатори на соодветни општи телесни активации. Покрај тоа, карактеризирајќи го поместувањето на ЕЕГ спектарот, мозочната брзина може ефикасно да се користи како општ мултигрупен биофидбек параметар, паралелно со поспецифичните малогрупни параметри.