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Clinical Efficacy of a New Automated Hemoencefalographic Neurofeedback Protocol

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Among the ongoing attempts to enhance cognitive performance, an emergent and yet underrepresented venue is brought by hemoencefalographic neurofeedback (HEG). This paper presents three related advances in HEG neurofeedback for cognitive enhancement: a) a new HEG protocol for cognitive enhancement, as well as b) the results of independent measures of biological efficacy (EEG brain maps) extracted in three phases, during a one year follow up case study; c) the results of the first controlled clinical trial of HEG, designed to assess the efficacy of the technique for cognitive enhancement of an adult and neurologically intact population. The new protocol was developed in the environment of a software that organizes digital signal algorithms in a flowchart format. Brain maps were produced through 10 brain recordings. The clinical trial used a working memory test as its independent measure of achievement. The main conclusion of this study is that the technique appears to be clinically promising. Approaches to cognitive performance from a metabolic viewpoint should be explored further. However, it is particularly important to note that, to our knowledge, this is the world’s first controlled clinical study on the matter and it is still early for an ultimate evaluation of the technique.

Keywords: HEG neurofeedback, clinical trial, cognitive reserve, brain metabolism, cognitive performance.

Entre los intentos en curso para mejorar el rendimiento cognitivo, uno emergente y todavía insuficientemente representado es el neurofeedback hemoencefalográfico (HEG). Este trabajo presenta tres avances relacionados con HEG neurofeedback para la mejora cognitiva: a) un nuevo protocolo HEG para la mejora cognitiva, así como b) los resultados de las medidas independientes de la eficacia biológica (mapas cerebrales EEG) extraídos en tres fases durante un año estudio de seguimiento de casos; c) los resultados del primer ensayo clínico controlado de HEG, diseñado para evaluar la eficacia de la técnica para la mejora cognitiva de población adulta y neurológicamente sana. El nuevo protocolo fue desarrollado en el marco de un software que organiza algoritmos de señales digitales en un formato de diagrama de flujo. Los mapas de cerebro fueron producidos a través de 10 registros cerebrales. El ensayo clínico utilizó un test de memoria de trabajo como medida independiente de sus logros. La principal conclusión de este estudio es que la técnica parece ser clínicamente prometedora. Los enfoques para el rendimiento cognitivo desde un punto de vista metabólico deben investigarse más a fondo. Sin embargo, es particularmente importante tener en cuenta que, a nuestro entender, este es el primer estudio clínico controlado sobre el tema en el mundo, y aún es pronto para una evaluación final de la técnica.

Palabras clave: neurofeedback HEG, ensayo clínico, reserva cognitiva, metabolismo cerebral, rendimiento cognitivo.

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During the last decades, several studies have addressed the dynamics of cognitive decline associated with aging. Currently, it is believed that the main sources of cognitive decline in cases where no evident neurological or psychiatric disorder have been noticed are represented by sub-clinical vascular and neurological conditions, whose course may take several years before identified (Stern et al., 2008). The deleterious impact of these conditions varies from individual to individual, in accordance with the resilience of the brain, also referred as the person’s “cognitive reserve” (CR).

In that sense, CR regards the idea that certain variables intermediate the relation between biological decay and cognitive decay. Also CR encompasses the perspective that different persons possess different resilience to natural aging and to insults to the neurocognitive system. Currently there is not a consensus about what feature should exactly be included within the boundaries of the concept (for a review: Valenzuela, 2008), but it is becoming clear that CR includes all of the following: characteristics intrinsically related to the brain wiring (Stern et al., 2008), the ability to use different neural networks in order to achieve similar results (Kalpouzos, Eustache, & Desgranges, 2008), and the educational/intellectual level (Kemppainen et al., 2008; Roe, Xiong, Miller, Cairns, & Morris, 2008; Starr & Lonie, 2008; Vance et al., 2008).

These factors are somehow interrelated, but not to the point of withholding several authors from stating that the educational/intellectual level is the core factor of the cognitive reserve ratio: “(…) yet cognitive reserve is more than brain anatomy. It is not simply a matter of brain size, the number of neurons per cubic millimeter, or even the number of synapses in a subject’s brain. The key factor in determining human cognitive reserve seems to be education” (Gundeman & Bachman, 2008, p. 671). For an independent comparison between the effects of intracranial volume and education which confirms the above perspective: Staff, Murray, Deary, and Whalley (2004).

But why, after all, is education so important? As Vance and collaborators (2008) state, the underlying brain mechanism is that continued learning efforts are intrinsically associated with ongoing mental stimulation of areas of the brain where the cells are most susceptible to insult and natural physical instability; that is, the prefrontal cortex (PFC); thus promoting neuroprotective phenomenon of plasticity in the PFC neuronal assemblies.

From that standpoint, it is reasonable to assume that enhancing the neurocognitive processes involved in cognitive demanding work should boost the neuroprotective effects of cognitive reserve. In order to study the above hypothesis, this article aims to introduce: 1. a new protocol for an emerging technique devoted to cognitive enhancement called applied hemoencefalography (HEG neurofeedback); 2. an independent measure of biological efficacy of the technique, using EEG brain maps in a one year follow up case study; 3. the results of a small ongoing controlled clinical trial that uses HEG neurofeedback with readings over three PFC sites, which evaluates the technique’s potential to aid CR, using an advanced working memory task as the independent measure of efficacy (test/retest interval for patients and controls = 1 week).

Study 1

Neurofeedback for Cognitive Enhancement: An Enhanced HEG Protocol

There are two basic ways to conceive brain signaling: a) by means of neurochemical signaling and; b) by means of neuronal assembly oscillatory behavior, that is, brain wave frequency. Both are intimately connected; frequency relies on patterns defined by the neurochemical activity of the cellular assemblies (specific brain circuits) and different compounds that affect neurotransmission in the brain (e.g., Ritalin) also affect EEG patterns, or better said, have their efficacy intrinsically tied to this ability (Loo, Teale, & Reite, 1999).

In that sense, the ultimate idea behind neurofeedback is the existence of a two way street between the oscillatory behavior of neuronal assemblies and the neurochemical signaling; that is, contrary to the idea that the oscillatory behavior is an emergent property of the cellular system, neurofeedback practice relies on the assumption that the manipulation of this higher level variable also produce effects in the signaling behavior, thus inducing molecular cascades that will generate long-term effects on brain physiology (for a review on behaviorally induced long-term plasticity in the human brain: Kandel, Schwartz, & Jessell, 2000).

Currently, there is much evidence supporting the durability of this effect (for fMRI evidence: Beauregard & Levesque, 2006), as well as a plethora of studies regarding cognitive enhancement. According to the most recent and carefully designed randomized, controlled clinical study testing the efficacy of neurofeedback for cognitive enhancement in attention deficit disorder (ADD), the effect size of the technique is .60, and the most recommended protocol are theta/beta training and slow cortical potential training (SCP) (Gevensleben et al., 2009).

Hemoencefalography neurofeedback (HEG) is a recent technique based on the intentional increase of cerebral blood flow oxygenation in defined sites of the brain (Tiniius, 2005); currently, there is no controlled study measuring its effect size in the literature.

There are two basic devices that can be used to achieve that goal: passive infrared HEG (pIR) and near-infrared HEG (nIR); while the former uses an infrared lens that serves as a brain thermometer to evaluate blood flow perfusion, the latter uses pulse oximetry: one LED with 650-1000 nm wavelength infrared that shines this light on the brain and,
by way of a light-measuring second diode, generates an indirect measure of blood oxygenation under the scalp sites were the diodes are located. Both methods are non-invasive.

The authors of this paper consider that the latter method is better than the former as it allows greater specificity in the isolation of the neuronal assemblies that are expected to be evaluated and trained (temperature cannot serve as a localist variable); and for its many previous applications in human biophysics; accordingly nIR HEG was used on the clinical trials that this paper presents and, heretofore will be the technology of our focus.

The rationale behind nIR HEG is that neuronal tissue metabolism relates to oxygen consumption (Buxton, Wong, & Frank, 1998) and, thus, to local hemoglobin levels. Hemoglobin, on the other hand, assimilates $\approx 650$ nm wavelengths, thus supporting an inverse relation between reflection levels and metabolism in the neuronal tissues shone by the diodes. Theoretically, this principle is supported by the Beer-Lambert Law: $A = \log \frac{I}{I_0} = a \cdot c \cdot d$, which reads as the attenuation $A$ of an incident light is proportional to the concentration $c$ of the compound in the solution and the optical path length $d$. (Gersten, Perle, Raz, & Fried, 2009, p. 259).

With that basis, HEG neurofeedback uses brain-computer-interface (BCI) in order to capture and reproduce real-time measures of encephalic oxygenated blood-flow perfusion, displayed on the computer as a guide towards the intentional control (herein: increase) of this variable and, thus, of the natural increase in brain metabolism at the training site.

The perspective of increasing cognitive capacity through the stimulation of prefrontal brain metabolism is supported by the generally accepted idea that the capacity to properly recruit brain networks in face of cognitive demands depends on available amounts of oxygenated blood in the related brain areas, in order to support the energetic demands of the process, both in health and disease states (Hosoda et al., 2010). Moreover, it is worth noting that several studies have provided evidences that the difficulty to solve a cognitive task is related to the degree to which a person needs to proportionally increase focal brain blood flow, therefore suggesting that training to increase blood flow capacity in the brain may affect the mind in a way that resembles of that of the most acute cognitive efforts (Larson, Haier, LaCasse, & Hazen, 1995).

Having said that, it is important to bear in mind that the evidences in favor of the idea that HEG neurofeedback lead to cognitive enhancement in health and disease are scarce and come mainly from conference papers (e.g, Dias & Deusen, 2010a, 2010b, 2010c). As we see it, this picture introduces new risks and opportunities, as it provides an unique chance to aid the development of the field of non-pharmacological approaches to cognitive enhancement.

Since HEG neurofeedback is directly related to the underlying metabolism, it is more ‘robust’ than EEG neurofeedback which is generally brain frequency specific. Also our clinical experience suggests that, due to the slow moving signal, as compared to EEG, the metabolic effect can be more “felt” by lay clients and, in particular the elderly, to gain faster control over their brains. The interface used offers a constantly increased demand, we believe leading to faster cognitive gains. Moreover, HEG sensors are also faster to install on the participant’s head (once practice is acquired) and finally, HEG, which uses light to measure is immune to electrical artifacts common to EEG, like muscular and electric noise (50-60W) from the electrical supply system. All together, these advantages suggest that it may overcome EEG neurofeedback as the main indication regarding non-pharmacological approaches to cognitive enhancement. On the other hand, we acknowledge the limitations of the field of neuropsychophysiology in regard to the provision of HEG protocols, which is specifically critical in relation to cognitive enhancement. According to our search of the literature, there is not a single study indexed in Pubmed presenting HEG protocols for cognitive enhancement.

This section aims to introduce a new HEG protocol for cognitive enhancement, as well as the results of independent measures of biological efficacy (EEG brain maps) extracted in three phases, during a one year follow up case study.

Method

Using the digital signal processing software BioExplorer, which organizes complex digital signal processing algorithms in a flowchart format, a new software-based biological signal processing circuit was developed. This circuit was used in an experimental case study, which took advantage of EEG brain maps as independent measures of neurophysiological change and durability said changes. The same circuit, once reinforced by the initial positive findings of the case study is then used, with no changes to the math or to the statistical output, in a biofeedback training model. The creation of the Design was the realized over a 4 month period by Adrian Van Deusen. The physiological signal processing was realized using neurofeedback-grade electroencephalograph unit manufactured by Minder Labs PL ACN company (Sidney, Australia). The model name is “A3”. It offers two independent EEG channels which measure signal at 256 samples per second with 10 bit resolution. The processed signal is sent to the receiving computer through 2.4 Ghz wireless transmission. A 60Hz electrical noise isolation “notch” filter is implemented with a range from 59 to 61Hz.

Results

The circuit below represents the statistical input portion of the “signal diagram” that was generated.

This circuit first calibrates the signal (Source 1 at top left, representing raw HEG signal input) to account for the hardware filters which were in fact developed for EEG recording (Expression 1 and Filter 1 seen in the upper part of Figure 1); from that starting point, the obtained measure (discrete value) becomes the basis for processing three
Figure 1. First level of the new HEG circuit.
Figure 2. Second level of the new HEG design.
phenomena in the Time domain; important in order to establish a fixed baseline and then calculate the percent of time that the real time Signal is greater than its own Baseline.

This is visible in the circuit image (figure 1) in the following fashion: Time Averages 2 and 3, as well as Expression 7 defines the baseline capture Time; Counter 1 in conjunction with Counter 2 generate a relative time measure defined in Expression 9; finally Expression 12 gathers time measures of specific gains or losses of HEG level in its feedback-dependant automation of the training process.

This statistical section of the design also receives inputs from the derived measure (filter 1) and establishes a Baseline (Expression 4). Discrete value and its averaged value are also be used as the Gain measure which is key in the Feedback section (figure 2). As with all biological measures, absolute values will vary considerably between persons, so in order to normalize the amplitude of the collected data between subjects, a simple calculation of Gain on Baseline was implemented. It is the same measure the experimental population is trained to increase in the clinical trial. This algorithm is normalized to be at “0” when Signal is equal to Baseline (Expression 2) and as stated, is used for all training purposes. As such, the Gain ratio is the principal measure with which we are working during the training, which is justified by the fact that it includes both Signal and Baseline in an elegant metric. More so, this biosignal processing circuit contains further developments implemented for greater automation of the data exportation and assessment. All bright green points export key measures in 1 second average intervals to a text-only number string that can be processed in Excel or other statistical processing software.

For best comprehension of these two images, note that the three key measures: HEG Level, baseline and gain the same as presented in figure 1 on the right side of the image, continue outlined in blue, now in figure 2, the three key measures are on the left side of the image to represent the panoramic spread. To the right of these three objects, the darker-grey display objects are aligned. These are the visible, audible and I.T. signals into which the biosignal is converted: numerical meters and graphs show realtime phenomena (Bar Graph and Meter column); short term and long-term trends are plotted (Trend 2); most interestingly, a biointerface is created to control variables like ‘screen size’, ‘volume’ and ‘brightness’ of DVD, VIDEO, MP3, CD as well as computer generated soundscapes. A direct interface with FLASH-based arcade games (developed by our team, led by Adrian Van Deusen) creates second level demands of functional mastery aligned with cerebral mastery. In this fashion, the layperson can observe the blood oxygenation in his or her prefrontal lobes while engaged with that information, as represented in a real time audio/visual environment in which he or she is comfortable yet which increases both demand and interest in obtaining self-mastery.

From the perspective that the interface is designed to receive a biological signal and return it to the participant in a form that he can interact with, it follows that this interface is closely-tied to the end goal of the training, which is the intentional control of increase in blood perfusion in the regions that are mostly related to cognitive reserve, that is, the PFC, specifically the DLPFC (10/20 sites: FP1 and FP2) and the MPFC (10/20 site: FPZ). In that sense, a practice as instructionally simple as the mental control of a multimedia computer interface (BCI) is directly dependent upon the extraction of the maximum potential of specific neural networks. Though not in itself an educational practice, this direct learning by the brain of its own localized metabolic processes follows and enhances the very same proposed neuroprotective mechanisms that seem to support CR (for a discussion: Boyle, Wilson, Schneider, Bienias, & Bennett, 2008; Hanyu et al., 2008; Vance et al., 2008).

Study 2

Assessment of HEG efficacy with EEG as an Independent measure: A one year follow-up case study

Accepting Education as the key factor in cognitive reserve theory, and further following theories on education as a stimulant to growth in density of neural networks in the PFC, HEG appears to be a means of stimulating that same physiological densification, while not requiring any cognitive educational material be assimilated in order to trigger said neuroplastic phenomenon.

We considered it important before embarking on the complexities of a controlled clinical trial to establish first indices that neuroprotective prefrontal cortex changes can be obtained through the use of HEG neurofeedback, independent of the cognitive gains that are being studied and whose initial findings are described in section 3.

Method

The subject was received by the psychology department in our clinic in Salvador, Bahia (Brazil) using standard intake procedures: a complete EEG normative baseline recording (NBR) was run and then, as per normal, a 10 session HEG PFC metabolic training protocol was realized. One year after completing HEG training, in which the subject did not train any more with those modalities, a second normative baseline recording was run. Data from the two NBR was compared, with emphasis in this study on the aspects related to prefrontal physiology and dynamics. Informed consent was obtained prior to the study. The data for the NBR analysis was obtained bilaterally from the following areas: prefrontal cortex; central sulcus...
(on the sensorimotor cortex); parietal cortex; temporal cortex and the sagittal inter-hemispheric fissure (in the terminology of the EEG technique: F3/F4; C3/C4; P3/P4; T3/T4; FZ/OZ) following a “mini-QEEG” methodology developed for low cost EEG assessment by The Learning Curve, Inc. of Lancaster, Pennsylvania (for more details, see: Dias & Deusen, 2011).

Results

Below we present the results obtained from one patient submitted to a clinical trial consisting of 10 sessions of HEG neurofeedback for both increased brain metabolism and cognitive enhancement. We chose to use brain maps (EEG) as our independent measure because EEG is the canonical basis of brain measure, with the largest database and is more easily replicable in a clinical setting than enhanced measures like fMRI. EEG thus provides a more immediate picture regarding possible neuroplastic effects. Moreover, we also considered the fact that EEG neurofeedback is an established technique among the non-pharmacological approaches to cognitive enhancement and that it is associated with long lasting changes of certain specific patterns of the EEG (Angelakis et al., 2007; Fox, Tharp, & Fox, 2005), which we applied as our guideline. In order to evaluate the efficacy of this alternative technique, regarding PFC dynamics, we analyzed data as following:

In figure 3 we present three types of data: Alpha asymmetry left/right frontal lobe (F3/F4); Rostral Alpha/Caudal Alpha and Rostral Beta/Caudal Beta. These readings show prefrontal dynamics across hemispheres which allow objective comparisons of mental state dynamics related to cognitive processing, sensory gating, among other subjective states related with CR. The Cohen’s d relative to the Alpha band activity is 2.4 and the effect-size r is .77. These results demonstrate a huge improvement in the Alpha band activity.

Further comparisons will be presented in figure 4.

Figure 4 presents the same variables that were discussed in figure 3, which we selected from the brain map that was done one year after the end of the training phase, in order to evaluate whether long lasting neuroplasticity might occur. The information presented in figures 3 and 4 demonstrate a clear change in predominant use of PFC sites in preference to other locations (Parietal-Occipital), wherein the pre-training recording shows in inversion of that predominance.

Two more independent measures relevant to brain physiology:

Figure 5 presents the most important independent measure in regard to the characteristics related to the brain wiring and its effects on cognitive ability: the Theta/Beta ratio in the PFC. Theta/Beta ratio is a simple mathematical description of the proportion of high frequency waves relative to low frequency waves in three different locations of the prefrontal lobe, left dorsolateral prefrontal cortex

**Figure 3.** Brain mapping profile of the participant in 22/02/08.
PFC activity one year after the end of the training phase (brain map date: 24/07/2009). Interhemispheric correlations show an average gain of 0.18 compared to pre-training, with two of the measures now in range. Rostral/Caudal relations are also improved, in association with PFC Beta activity increases in both hemispheres.

Figure 4. Brain mapping profile of the participant right after the end of the trial in 24/07/08.

Theta/Beta relationships in the pre-training baseline (brain map date: 24/08/2008). Theta waves are predominant in the PFC. Subject also presents inverse Theta/Beta activation in PFC comparing eyes open to the cognitive task. Average Alpha frequency: 8.56 Hz.

Figure 5. Pre-training/post-training follow-up profiles.
(DLPFC), the right DLPFC and the cingulate gyrus. Moreover, comparative measures of the average Alpha frequency are also presented due to their correlation with brain maturation and with functional memory ability as well as motor reaction time. In this fashion, the authors seek to demonstrate findings on the efficacy of HEG in this case study by means of two independent yet complementary EEG metrics of long term modification of PFC physiological potential.

### Study 3

**Assessment of Cognitive Gains Related to PFC HEG Neurofeedback Training: Preliminary Findings from a Small Controlled Clinical Study**

As we have argued—and had suggested by our small follow up study—HEG neurofeedback is in our view, a promising technique for cognitive enhancement. However, we searched Pubmed and Google Scholar with several keywords related to HEG neurofeedback and could not find a single controlled clinical trial applying the technique.

This section aims to present the results of the first controlled clinical trial of HEG neurofeedback in the world, designed to assess the efficacy of the technique for cognitive enhancement of an adult and neurologically intact population.

### Method

This study was approved by the local university ethic committee and all participants signed the informed consent term. In order to make this experiment as comprehensive as possible, we chose to present the detailed description of the methods and the raw data that support our results elsewhere, on the following website (Dias, 2010), which we guarantee to maintain operational until 01/01/2013. Below we present the key methodological variables.

*N = 16; 8 subjects in the condition and 8 controls.*

Number of sessions of PFC HEG neurofeedback: 3.

These trials did not use full-blown placebo methods, since our concern regarding the controls only related with the stability of performance in the test/retest (working memory). In order to avoid bias related with different levels of self-confidence in both groups, controls were told that they could ‘naturally improve’ during the test/retest period.


**Description of the network memory test:** The network memory task cross-evaluates two measures of performance; the number of recollected items and the order within the recalled sequences; the formula to calculate performance includes the mean number of recollected items and the number of necessary permutations in order to turn the sequence that was created into the ‘correct sequence’ (Kendal tau). The task involves two stages: 1. assorting 12 photographic figures representing human faces by preference; 2. recalling predefined sections of the first ordering. A total of three sections were used and the exposure time to the original sequence (the period during which the participants were allowed to freely move the figures in order to create their preferred sequence) was limited to a maximum time of 1 minute.

### Results

Below we present first a table with the neurological results, in which HEG columns cite absolute blood oxygenation averages (SpO2) for each of the three training locations; Gain columns represents the percent-gain over a baseline that was established 30 seconds into the training period based upon the last 20 second average SpO2 level (creating both a standardized metric and also a training goal—to overcome ones own baseline); finally and most importantly to overall analysis, the average gain on baseline of the PFC. Minimum gain was 4.66% more SpO2,

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<th>HEG 2</th>
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achieved by a 59 year old female. Maximum gain was 7.89% more SpO2 obtained by a 33 year old female. Among the 8 participants (1st column; letter ‘P’), all produced inter-session gains in blood flow perfusion, while six had absolute gains from the first to the third section, suggesting that they are evolving consistently.

The second table presents the working memory task test/retest results which were the data that we gave principal emphasis in order to assess the possible functional gains of mere pre-frontal lobe training designed to generate a similar cerebral response as would be expected from education.

In the working memory task, seven improved, while only three improved in the control group. Analyzing the scores, the mean and standard deviation prior to session were 4.45 and 1.02, respectively. After the sessions the mean and standard deviation were 4.7 and 1. These results imply a Cohen’s d of .25 and effect-size r of .12, indicating a moderate improvement. We also use Mann-Whitney non-parametric test to verify whether the mean improvement for the active group surpassed that of the control group; this procedure led to \( p = .0465 \). Although these are exciting results, the authors stress that this statistical analysis should not be overestimated since our sample is not very impressive.

The supplementary material presents details of the performances of both groups (Dias, 2010).

It is worth noting that the only participant who did not respond to the HEG training with an improvement in the working memory task, was patient 3, who also received the highest score in the BDI (23 points in the scale) and thus was diagnosed with mild depression. In that regard, it is up to consideration whether cognitive enhancement with HEG neurofeedback might be blocked by affective components, or if this was just a coincidence.

### Conclusions

This paper introduces a new protocol to increase blood flow perfusion in the prefrontal lobe using HEG neurofeedback, which was used in a one year follow up study (one volunteer), and in a small clinical trial (\( N = 8 \)). The results that were found suggest that the technique is promising. However, it is important to note that these are preliminary findings. Further studies are needed in order to properly define the technique’s reliability as well as the specific place that our protocol deserves in this field of cognitive enhancement.

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To the authors, a most interesting finding was obtained in recognizing correlates of electric (EEG) and metabolic dynamics in the brain. It is suggestive that cognitive performance and CR have their physiological basis settled not only in the electric and neurochemical properties of the brain, but in the hematic properties as well. This idea challenges tacit principles in the field of cognitive psychology and cognitive neuroscience, expressed in the performance and CR from a neurochemical viewpoint, suggesting new venues in clinics and experimental research.

References


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